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MANUFACTURING METHODS AND TECHNOLOGY
(MANTECH) PROGRAM

SERVICE LIFE DETERMINATION FOR THE UH-60A (BLACKHAWK) HELICOPTER ELASTOMERIC BEARINGS

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April 1980

FINAL REPORT

Contract No. DAAG46-78-C-0029

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AVIATION RESEARCH AND DEVELOPMENT COMMAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The contract with AMMRC calls for developing an improved method of predicting the service life of elastomeric bearings in general with specific reference to the Blackhawk main rotor bearings. One object of this study is to develop a correlation between a bearing that has sustained some endurance damage and its remaining service life based on its appearance. The second objective is to develop an analytical capability to predict the

Block No. 20

ABSTRACT

service life of bearings without the necessity for testing.

An endurance rating for an appropriate elastomer is determined by testing a series of 13 test specimens. The test specimen and the Blackhawk main rotor bearings are analysed by finite element methods. A procedure is developed for relating the complex strain history of the Blackhawk bearings to the endurance data so that a life prediction can be made for the main rotor bearings without testing. The main rotor bearings are then tested and experimental and analytical results compared.

FOREWARD

This project was accomplished as part of the U. S. Army Aviation Research and Development Command Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army Material. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U. S. Army Aviation Research and Development Command, ATTN: DRSAV-EXT, P. O. Box 209, St. Louis, MO 63166.

The work described in this report was accomplished under a contract let and monitored by the U. S. Army Materials and Mechanics Research Center (DAAG46-78-C-0029).

PREFACE

The author is grateful for the contributions of the following individuals:

- Dr. Barnard Halpin -- Coordination of this project for the Army Material and Mechanics Research Center.
- J.P. Morley -- Coordination of this project for CR Industries.
- E.M. Skroch -- Supervision and reporting of test work.
- T.G. Mueller -- Material recommendations, testing and reporting.
- S. Rengarajan -- Finite element modeling, data reduction and general assistance.
- Mrs. Olga Kriz -- Typing this report.

INDEX OF REPORT SECTIONS

SECTION 1.

OUTLINE OF OBJECTIVES

OUTLINE OF OBJECTIVES

The main rotor elastomeric bearings used on the Blackhawk model helicopter are flight critical hardware. It is imperative that their service life be predictable and well known. Correctly applied elastomeric bearings should degrade gradually and give some visual indication of their remaining life. Blackhawk main rotor bearings are to be replaced on an "on condition basis". It is, therefore, important to be able to correlate the appearance of a bearing with its remaining service life.

Under this contract two sets of Blackhawk main rotor bearings (see Figs. 1, 2 & 3) will be endurance tested to Sikorsky Aircraft's load and motion specification S.E.S. 701059 Rev. 4. Fig. 4, 5 & 6 show the proposed blocks of endurance testing that will be used. During the test the free heights, spring rates and photographic appearance of the bearings will be recorded. The unaccelerated test will be run for the equivalent of 1500 hrs. of helicopter flight or until a red line value is reached for any of the above. Fig. 7

& 8 are basic line drawings of the existing test rigs that will be used for this testing. Photographs of these rigs are shown in Fig. 9 & 10.

Because of the high cost of running full scale endurance tests, it is very desirable that a method be developed for predicting the service life of these bearings and all military elastomeric bearings in general. The most reliable tool that we have at this point for making these predictions is a complete analysis of the strain in the elastomeric bearings by finite element analysis (F.E.A.) followed by a correlation of the resulting strain histories to basic endurance data. Because of the complexity of these bearings, it is usually found that some modeling compromises must be made in order that the problem can be handled on even the largest available computers. Our experience on the other hand, shows that these compromises must be intelligently made, for the results of F.E.A. are no better than the model from which they are generated.

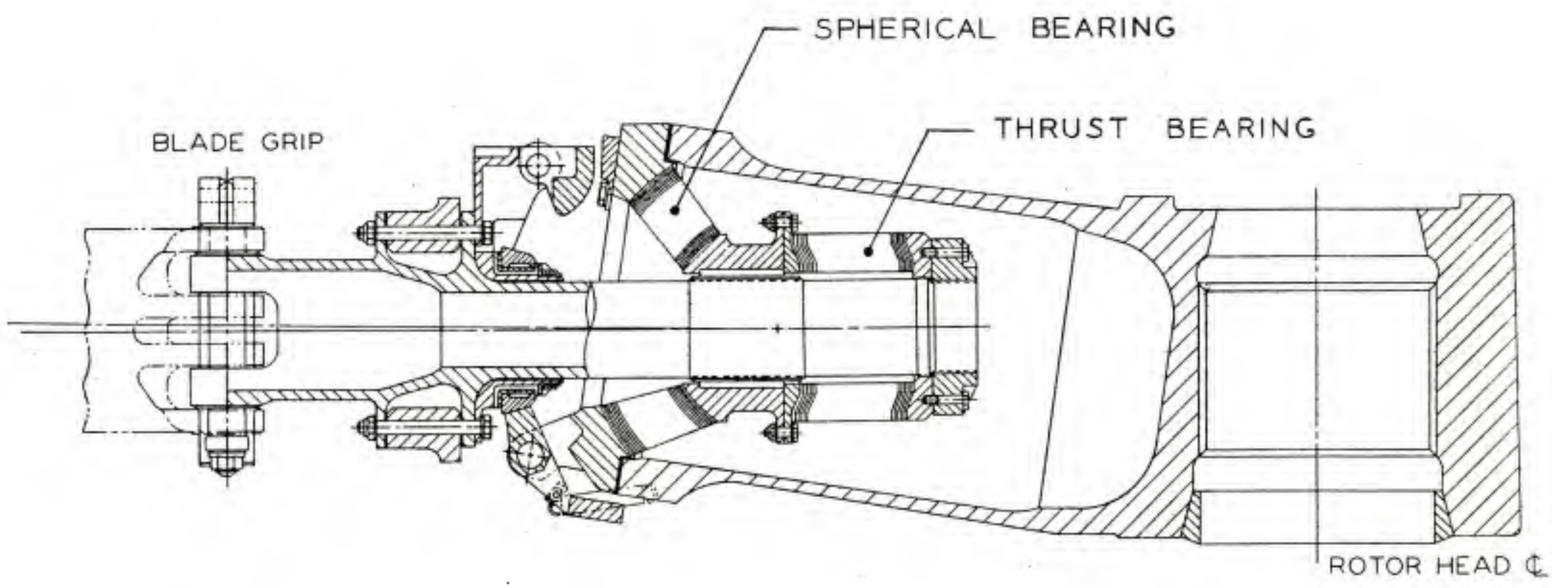
In order to get this project started on a firm basis, a relatively simple endurance test specimen will be designed. The simplicity of this specimen will allow a F.E.A. to be performed with a fine grid mesh with relatively few modeling compromises. This model will be used first to study modeling compromises that can be made so that good results can be

obtained from a relatively coarse mesh model. This skill will be needed later to model the full scale Blackhawk elastomeric bearings for F.E.A. Next, thirteen endurance test specimens will be fabricated and tested for "first damage" according to the tentative test plan in Fig. 11. An endurance life rule will be generated for the elastomer from the data from these tests. A F.E.A. will be made for the full scale Blackhawk main rotor elastomeric bearings and the strain history in the full scale endurance test bearings generated. In generating this strain history it will at first be assumed that strains can be combined as time-space vectors and that "first damage" can be predicted by Miner's Rule for accumulated damage. The basic elastomer endurance life data previously generated will be used to predict the main rotor E.B. "first damage" point. This "first damage" point will be correlated with full scale testing.

Elastomeric bearings are in general three-dimensional bodies loaded in three-dimensional space. Because of computational limitations it is usually necessary to apply a finite element program that was written to analyze axisymmetric objects of revolution that are loaded either axisymmetrically or by simple rotational loading rules such as a sine loading rule, but not both. These restrictions are not a severe handicap in the

case of the thrust bearing and its loading system (see Fig. 3). For the spherical bearing (see Fig. 2) it will not be possible to include a complete loading system in any one computer solution. The elastomer strains from several runs that form a complete loading case must be combined as time-space vectors. This technique yields useful results in the case of elastomer strains, but can not be used to find the maximum shell stress in the spherical bearing. This maximum stress has been found experimentally with strain gages to occur when the combined centrifugal force (C.F.) and cocking rotation (lead-lag or flap) is applied to the bearing.

The two principal modes of failure of elastomeric bearings are elastomer endurance degradation and metal fatigue. The major effort in this project will be directed towards predicting elastomer damage. The endurance test on full scale bearings will, however, yield valuable endurance data on metal shells. To show the usefulness of F.E.A. in predicting metal fatigue in some types of elastomeric bearings a special fatigue test will be run on a thrust bearing that can be completely analyzed.



BLACKHAWK MAIN ROTOR BEARINGS LAYOUT

FIG. 1

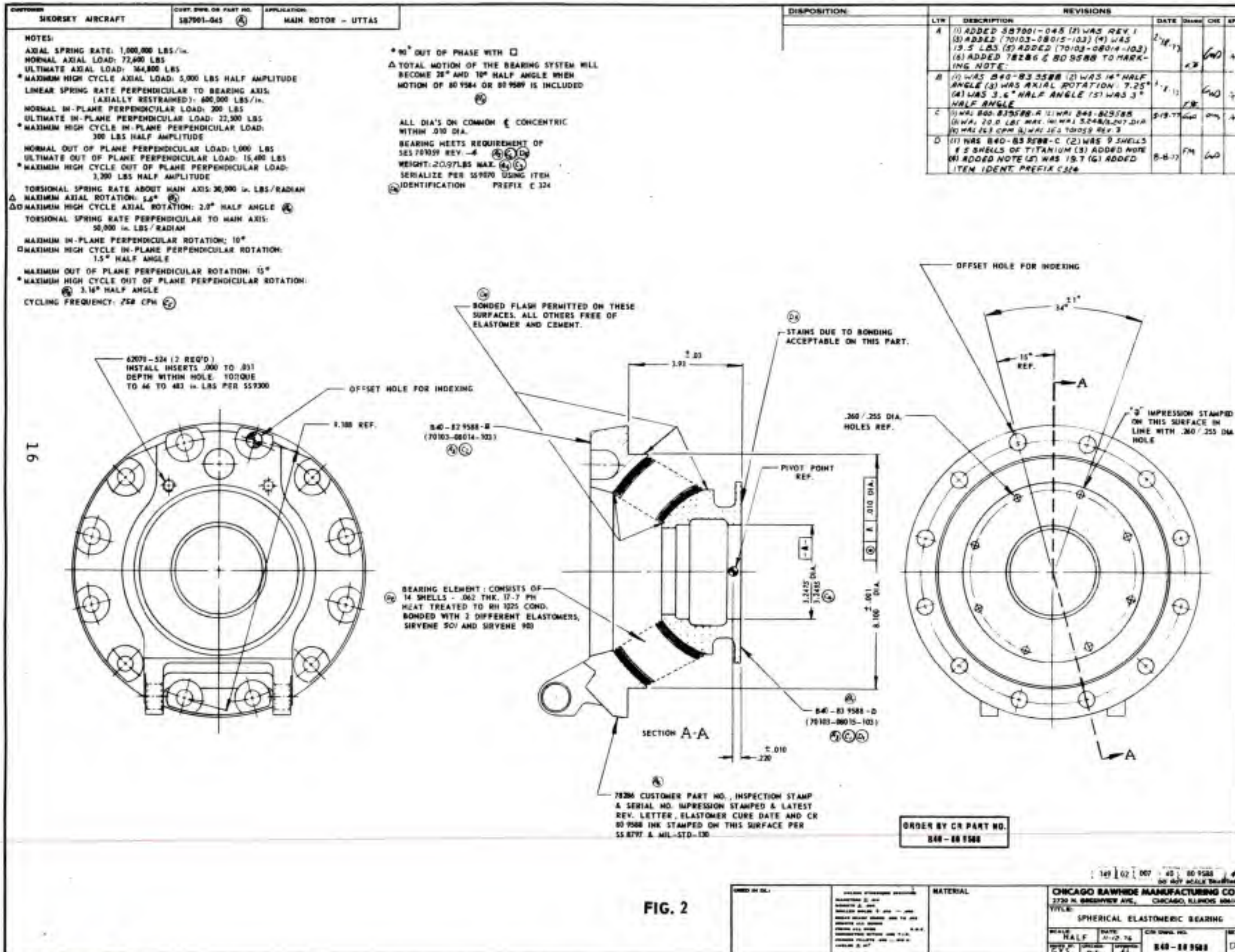

CUSTOMER: SIKORSKY AIRCRAFT
CUST. DWG. OR PART NO.: SB7001-045 (A)
APPLICATION: MAIN ROTOR - UTTAS
DISPOSITION:
REVISIONS
LTR | DESCRIPTION | DATE | DRAWN | CHK | APPR
A | (1) ADDED SB7001-045 (2) WAS REV. I (3) ADDED (70103-08015-103) (4) WAS 19.5 LBS (5) ADDED (70103-08014-103) (6) ADDED 78286 & 80 9588 TO MARKING NOTE
B | (1) WAS 840-83 9588 (2) WAS 14° HALF ANGLE (3) WAS AXIAL ROTATION: 7.25° (4) WAS 3.6° HALF ANGLE (5) WAS 3° HALF ANGLE
C | (1) WAS 840-83 9588-A (2) WAS 840-82 9588 (3) WAS 20.0 LBS MAX. (4) WAS 3.248/3.247 DIA (5) WAS 263 CPM (6) WAS SES 701059 REV. 3 | 5-19-77
D | (1) WAS 840-83 9588-C (2) WAS 9 SHELLS & 5 SHELLS OF TITANIUM (3) ADDED NOTE (4) ADDED NOTE (5) WAS 19.7 (6) ADDED ITEM IDENT. PREFIX C324 | 8-8-77
NOTES:
AXIAL SPRING RATE: 1,000,000 LBS/in.
NORMAL AXIAL LOAD: 72,600 LBS
ULTIMATE AXIAL LOAD: 164,800 LBS
* MAXIMUM HIGH CYCLE AXIAL LOAD: 5,000 LBS HALF AMPLITUDE
LINEAR SPRING RATE PERPENDICULAR TO BEARING AXIS: (AXIALLY RESTRAINED): 600,000 LBS/in.
NORMAL IN-PLANE PERPENDICULAR LOAD: 300 LBS
ULTIMATE IN-PLANE PERPENDICULAR LOAD: 22,500 LBS
* MAXIMUM HIGH CYCLE IN-PLANE PERPENDICULAR LOAD: 300 LBS HALF AMPLITUDE
NORMAL OUT OF PLANE PERPENDICULAR LOAD: 1,000 LBS
ULTIMATE OUT OF PLANE PERPENDICULAR LOAD: 15,400 LBS
* MAXIMUM HIGH CYCLE OUT OF PLANE PERPENDICULAR LOAD: 3,300 LBS HALF AMPLITUDE
TORSIONAL SPRING RATE ABOUT MAIN AXIS: 30,000 in. LBS/RADIAN
△ MAXIMUM AXIAL ROTATION: 5.6°
△□ MAXIMUM HIGH CYCLE AXIAL ROTATION: 2.0° HALF ANGLE
TORSIONAL SPRING RATE PERPENDICULAR TO MAIN AXIS: 50,000 in. LBS/RADIAN
MAXIMUM IN-PLANE PERPENDICULAR ROTATION: 10°
□ MAXIMUM HIGH CYCLE IN-PLANE PERPENDICULAR ROTATION: 1.5° HALF ANGLE
MAXIMUM OUT OF PLANE PERPENDICULAR ROTATION: 15°
* MAXIMUM HIGH CYCLE OUT OF PLANE PERPENDICULAR ROTATION: 3.16° HALF ANGLE
CYCLING FREQUENCY: 258 CPM
* 90° OUT OF PHASE WITH □
△ TOTAL MOTION OF THE BEARING SYSTEM WILL BECOME 38° AND 10° HALF ANGLE WHEN MOTION OF 80 9584 OR 80 9589 IS INCLUDED
ALL DIA'S ON COMMON ℄ CONCENTRIC WITHIN .010 DIA.
BEARING MEETS REQUIREMENT OF SES 701059 REV. -4
WEIGHT: 20.97 LBS MAX.
SERIALIZE PER SS9070 USING ITEM IDENTIFICATION PREFIX C 324
62070-524 (2 REQ'D) INSTALL INSERTS .000 TO .031 DEPTH WITHIN HOLE. TORQUE TO 46 TO 483 in. LBS PER SS9300
OFFSET HOLE FOR INDEXING
9.188 REF.
BONDED FLASH PERMITTED ON THESE SURFACES. ALL OTHERS FREE OF ELASTOMER AND CEMENT.
840-82 9588-B (70103-08014-103)
BEARING ELEMENT: CONSISTS OF 14 SHELLS - .062 THK. 17-7 PH HEAT TREATED TO RH 1025 COND. BONDED WITH 2 DIFFERENT ELASTOMERS, SIRVENE 501 AND SIRVENE 903
STAINS DUE TO BONDING ACCEPTABLE ON THIS PART.
PIVOT POINT REF.
.260/.255 DIA. HOLES REF.
840-83 9588-D (70103-08015-103)
SECTION A-A
±.010
78286 CUSTOMER PART NO., INSPECTION STAMP & SERIAL NO. IMPRESSION STAMPED & LATEST REV. LETTER, ELASTOMER CURE DATE AND CR 80 9588 INK STAMPED ON THIS SURFACE PER SS 8797 & MIL-STD-130
OFFSET HOLE FOR INDEXING
15° REF.
"0" IMPRESSION STAMPED ON THIS SURFACE IN LINE WITH .260/.255 DIA HOLE
ORDER BY CR PART NO. 840-80 9588
MATERIAL
DO NOT SCALE DRAWING
CHICAGO RAWHIDE MANUFACTURING CO.
2730 N. GREENVIEW AVE., CHICAGO, ILLINOIS
TITLE: SPHERICAL ELASTOMERIC BEARING
SCALE: HALF
CR DWG. NO. 840-80 9588
REV. D

FIG. 2

CUSTOMER	CUST. DWG. OR PART NO.	APPLICATION
SIKORSKY AIRCRAFT	SB7002-045	MAIN ROTOR - UTTAS

INTERNAL SPLINE DATA
30° INVOLUTE FULL FILLET SIDE BEARING

DIAMETRAL PITCH	24/48
NUMBER OF TEETH	64
PITCH DIAMETER	2.6667
BASE CIRCLE DIAMETER	2.3094
CHORDAL TOOTH SPACE (EFFECTIVE)	.0644-.0654
DIM. BETWEEN .0720 DIA. PINS (BASED ON ACTUAL TOOTH SPACE)	2.5689/2.5671
MAJOR DIAMETER	2.7417/2.7507
MINOR DIAMETER	2.6250/2.6300
MIN. T.I.F. DIAMETER	2.7083
MAX. ACCUMULATED SPACING ERROR (BETWEEN ANY 2 TEETH)	.0015
MAX. TOOTH TO TOOTH SPACING ERROR	.0004
MAX. LEAD ERROR	.0002
MAX. INVOLUTE PROFILE ERROR AT T.I.F.	+.0004 -.0006
AT TIP	+.004 -.0006
MIN. FILLET RADIUS (APPROX.)	.019

NOTES:

AXIAL SPRING RATE:	800,000 LBS./in.
NORMAL AXIAL LOAD:	72,600 LBS.
ULTIMATE AXIAL LOAD:	164,800 LBS.

*MAXIMUM HIGH CYCLE AXIAL LOAD: 700 LBS. HALF AMPLITUDE
TORSIONAL SPRING RATE: 7000 in. LBS. / RADIAN
△*MAXIMUM HIGH CYCLE AXIAL ROTATION: 8.0° HALF ANGLE
△MAXIMUM AXIAL ROTATION: 22.4°
CYCLING FREQUENCY: 363 CPM
*90° OUT OF PHASE TO EACH OTHER
△TOTAL MOTION OF THE BEARING SYSTEM WILL BECOME 28° AND 10° HALF ANGLE WHEN MOTION OF 80 9588 IS INCLUDED.

△ ALUMINUM ALLOY 7075T73 PER QQ-A-367 (OR QQ-A-250/12 (5) OR QQ-A-225/9 ALUMINUM ALLOY 7075-T651 PROCESS PER SS 8043 TO 7075-T73) ANODIZED PER MIL-A-8625 TYPE I OR II. BREAK ALL SHARP EDGES .005 - .015 RADIUS.

△ MIL-T-9046 TYPE 3 COMP. C OR MIL-T-9047 TYPE 3 (5) COMP. A. 6 AL-4V TITANIUM ALLOY ANNEALED. AFTER MACHINING SHOT PEENED ALL OVER TO AN INTENSITY OF .012 A USING STEEL SHOT. PER SS-8766 EXCEPT SHOT PEEN SPLINE TO AN INTENSITY OF .006 A USING STEEL SHOT AND DID NOT SHOT PEEN .250 THD.

ALL DIA'S ON A COMMON CENTER-LINE CONCENTRIC WITHIN .010 DIA.

BEARING MEETS REQUIREMENTS OF SES 701059-REV. 4 (5)

ALL DRILL POINT ANGLES 100° - 150°

GAGING OF THREADS SHALL BE ACCOMPLISHED IN ACCORD WITH METHOD A PER MIL-S-8879.

BREAK ALL SHARP EDGES .030 - .060 RADIUS UNLESS OTHERWISE SPECIFIED. FOR INTERNAL SPLINE, BREAK SHARP EDGES .005 - .015 RADIUS.

WEIGHT: 7.1# LBS. MAX. (5)

△ 125 ALL OVER. SS 5100 SHALL APPLY FOR HOLES UNLESS OTHERWISE INDICATED. AREAS OF TRANSITION SHALL CONFORM TO THAT SPECIFIED FOR THE ROUGHEST ADJACENT FINISHED AREA UNLESS OTHERWISE INDICATED.

DISPOSITION:

REVISIONS

LTR	DESCRIPTION	DATE	DRAWN	CHK	APPR
D	(1) DRWG. B40-80 9589 OF 8-24-76 REV. "C" OF 5-26-77 REDRAWN WITH CHANGES (2) ADDED "OR QQ-A-250/12 OR QQ-A-225/9 AL ALY 7075-T651 PROCESS PER SS 8043 TO 7075-T73" & "TYPE II" (3) ADDED "OR MIL-T-9047 TYPE 3 COMP. A (4) WAS REV. 3 (5) WAS 72 LBS. MAX (6) WAS .630 ±.050 (7) ADDED "SERIALIZE PER SS 8070 USING ITEM IDENT. PREFIX C325" (8) ADDED "OR CEMENT" (9) ADDED NO FLASH OR CEMENT PERM."	8-8-77	BF	GJO	

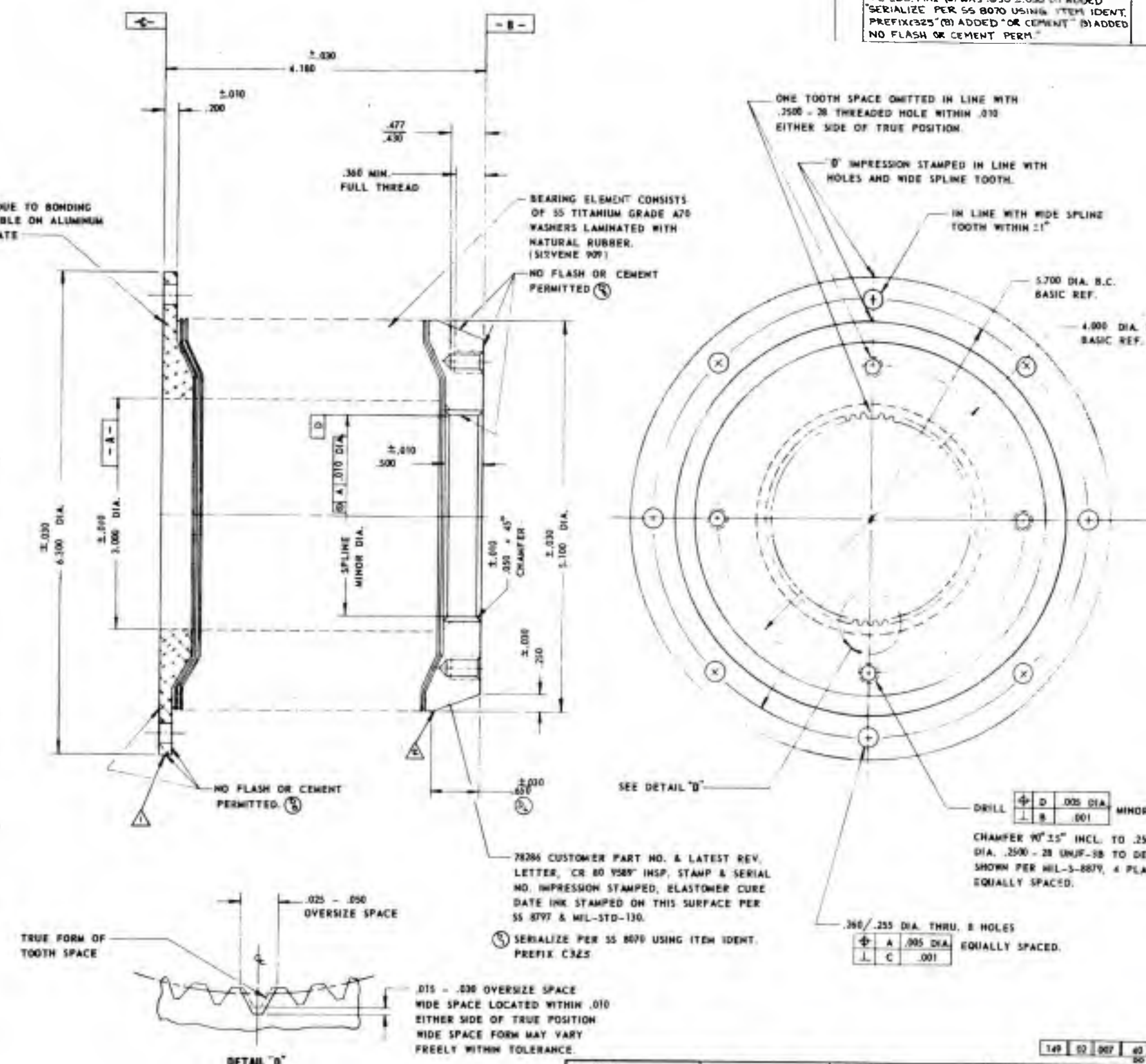


FIG. 3

MATERIAL

149 | 02 | 007 | 40 | 80 9589 | 4
DO NOT SCALE DRAWING

CHICAGO RAWHIDE MANUFACTURING CO.
3720 N. GREENVIEW AVE., CHICAGO, ILLINOIS 60614
TITLE: THRUST ELASTOMERIC BEARING MAIN ROTOR
SCALE: FULL & 4X | DATE: 8-8-77 | C/R DWG. NO. B40-80 9589 | REV. D
DRAWN BY: BF | CHECKED: GJO

K&E CO. 10-8194

BLACKHAWK MAIN ROTOR E.B. ENDURANCE LIFE TEST BLOCK I

S.E.S. CONDITION NO. (S.E.S.Rev.4 of 4-4-74)	TIME HRS. PER 100 HR. BLOCK	CONE ANGLE Θx	FLAP ANGLE $\pm\Theta x$	HUNT ANGLE		PITCH ANGLE		AXIAL LOAD Tc	PERPENDICULAR LOAD (POUNDS)	
				θy	$\pm\theta y$	θz	$\pm\theta z$		Vn	±Vn
10	1.5^0	-4.32^0	5.0^0	0	1.5^0	-5.72^0	6.49^0	68,000 LBS.	1,026	1,196
1, 30, 50 & 57	3.8		4.5							
9, 28, 29, 51 & 58	17.9		4.0							
8, 27, 33	13.1		3.65							
38 & 40	3.0		3.5							
20 & 26	2.4		3.4							
19, 21 & 39	9.2		3.3							
18	9.1		3.15							
25, 34 & 37	4.6		2.97							
7, 17, 31 & 35	14.4		2.9							
16 & 22	2.1		2.72							
2, 24 & 36	2.5		2.59							
6, 11, 12, 15 & 23	5.6		2.5							
13 & 14	2.4		1.4							
3	1.2		1.44							
32	3.0		1.3							
4 & 5	2.9	-4.32	1.2	0	1.5	-5.72	6.49	68,000	1,026	1,196

Total hrs. per hr. block 98.92

Cycling Frequency: 263 CPM.
Phasing: $\pm\theta y$ & $\pm\theta z$ in phase, $\pm\theta x$ & ±Vn both out of phase with θz by 90^o
θz & $\pm\theta z$ proportioned between the thrust and spherical bearings according to their relative spring rates.

FIG. 4

BLACKHAWK MAIN ROTOR E.B. ENDURANCE LIFE TEST BLOCK II

S.E.S. CONDITION NO. (S.E.S.Rev.4of4-4-74)	CYCLES @ 258 RPM/100 HR.	CONE ANGLE θx	FLAP ANGLE $\pm\theta x$	HUNT ANGLE		PITCH ANGLE		AXIAL LOAD	PERPENDICULAR LOAD (POUNDS)	
				θy	$\pm\theta y$	θz	$\pm\theta z$		Vn	±Vn
41	1.5	-3.18^0	12.0^0	2.9^0	1.5^0	3.60^0	14.4^0	68,000 LBS.	1,608	3,188
42	3	-3.18	11.0	2.9		3.70	13.5		1,608	3,188
43	6	-2.69	10.0	2.7		3.90	12.5		1,598	3,128
44	36	-2.09	9.0	2.4		4.10	11.5		1,579	2,989
45	77	-1.46	8.0	2.1		4.25	10.5		1,540	2,870
46	340	-0.86	7.0	1.8		4.40	9.5		1,500	2,770
47	1,548	0.55	6.0	1.1		4.55	8.5		1,431	2,334
48	1,703	1.33	5.5	0.8		4.60	8.0		1,373	2,176
49	4,644	2.0	5.0	0.4		4.70	7.5		1,334	1,979
52	1.5	0.55	8.0	1.1		3.60	14.4		1,470	2,503
53	29	1.11	7.0	0.9		3.85	12.6		1,431	2,335
54	433	1.34	6.0	0.6		4.15	10.9		1,373	2,177
55	1,858	2.11	5.5	0.4		4.30	10.0		1,354	1,980
56	6,037	2.45	5.0	0.2	1.5	4.45	9.1	68,000	1,315	1,891

Fig. 5

BLACKHAWK MAIN ROTOR E.B. ENDURANCE LIFE TEST BLOCK III

CONDITION (S.E.S.Rev.4 of 4-4-74)	CYCLES/ 100 HR.	CONE ANGLE θx	FLAP ANGLE $\pm\theta x$	HUNT ANGLE		PITCH ANGLE(1)		AXIAL LOAD (LBS.)		PERPENDICULAR LOAD (POUNDS)	
				θy	$\pm\theta y$	θz	$\pm\theta z$	Tc	±Tc	Vn	±Vn
Start/Stop (2)	300	-8.5^0	0	0	$\pm10^0$	11.5^0	0	1,300	0	0	1,000
On/Off Centrifugal	200	0	0	0	0	11.5	0	34,000	34,000	0	0
Control Check	400	-8.5	0	0	0	-3.5	24.5	1,300	0	4,025	0
Rotor Overspeed	100	0	0	0	0	11.5	0	41,000	41,000	0	0

Cycling Frequencies: Will be between 1 & 10 CPM.

1) θz & $\pm\theta z$ proportioned between the thrust and spherical bearings according to their relative spring rates.

2) $\pm\theta y$ & ±Tc in phase for Start/Stop test.

FIG. 6

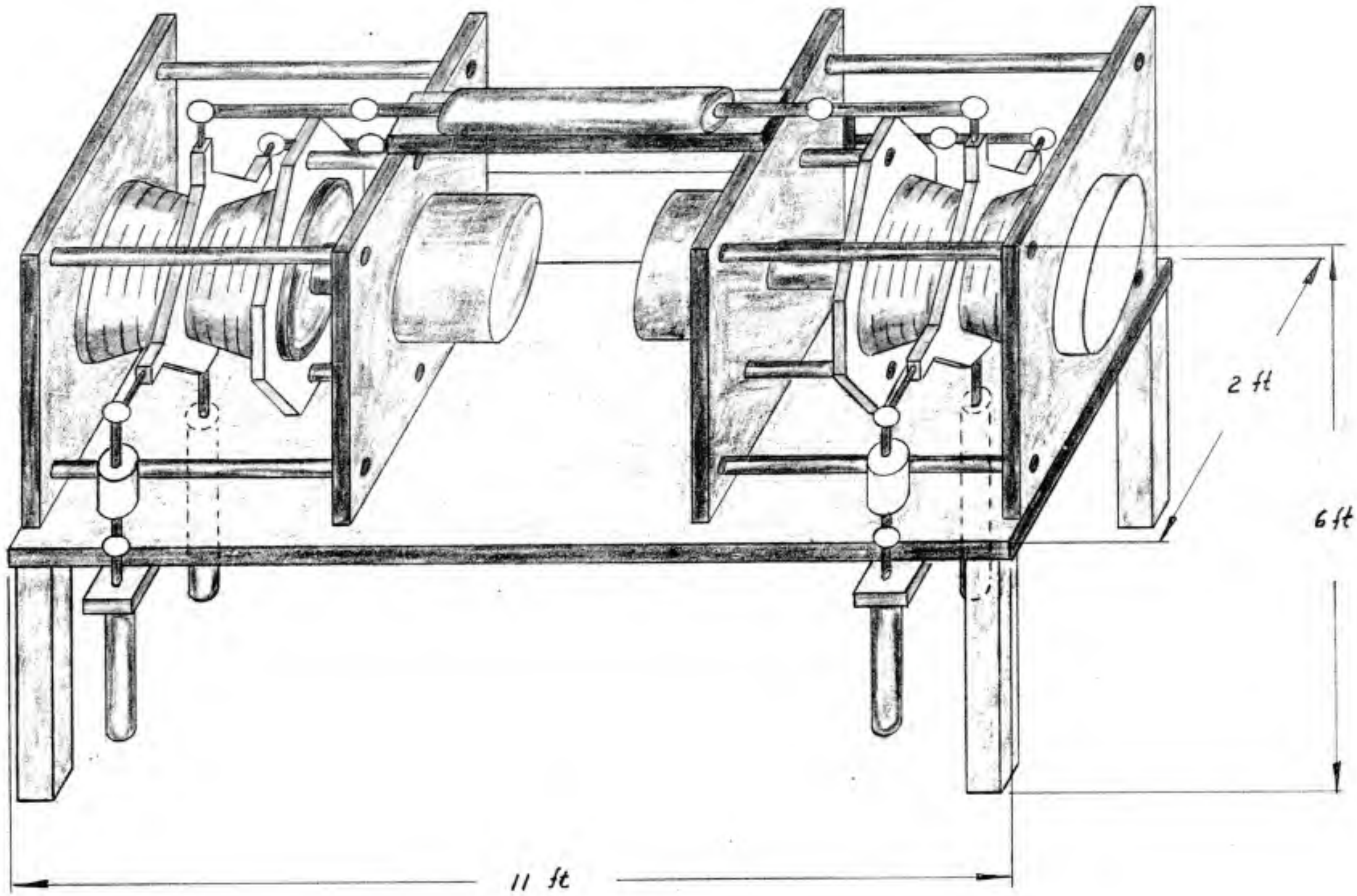


FIG. 7 BLADE RETENTION BEARING FATIGUE TEST STAND

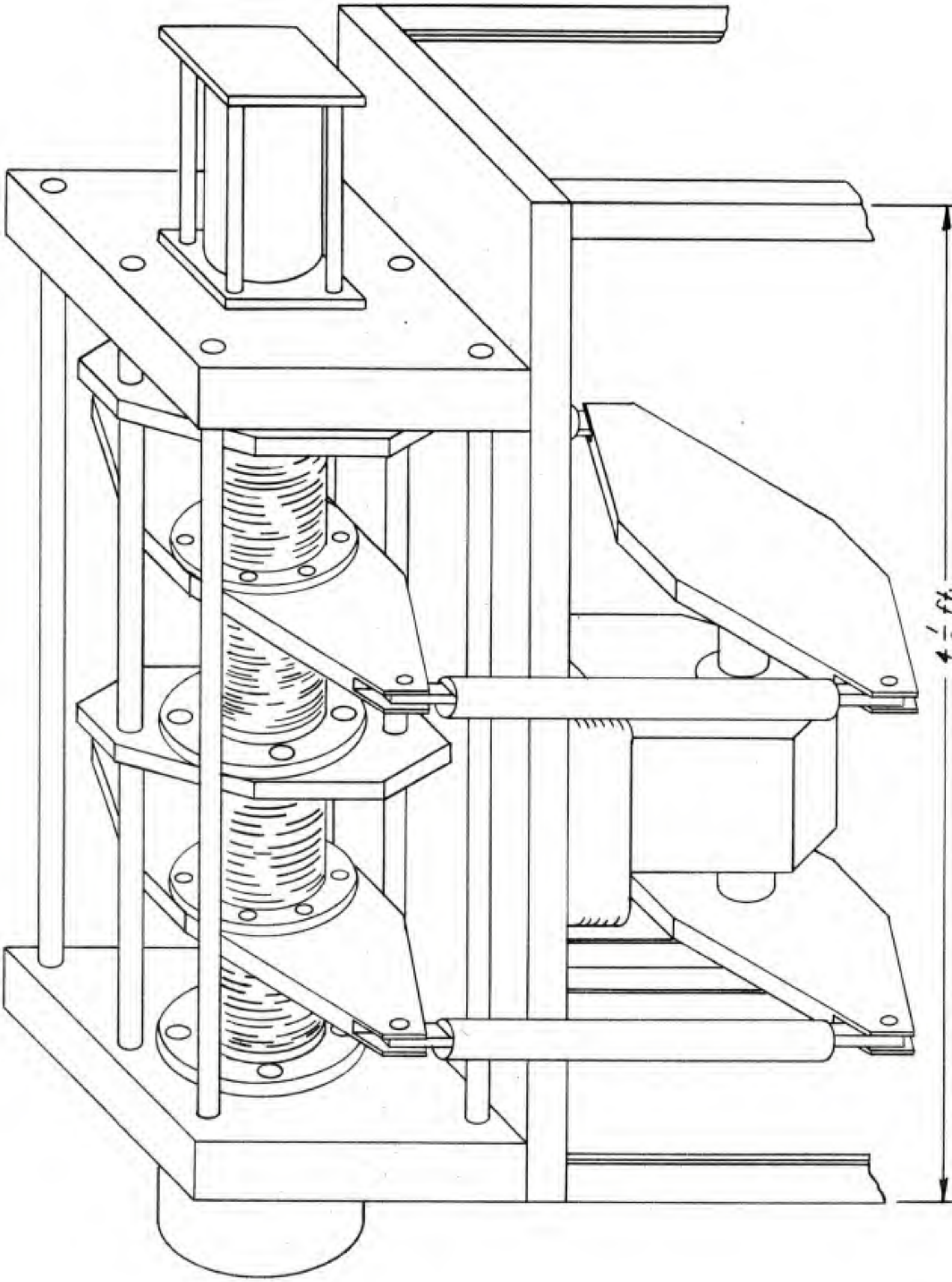
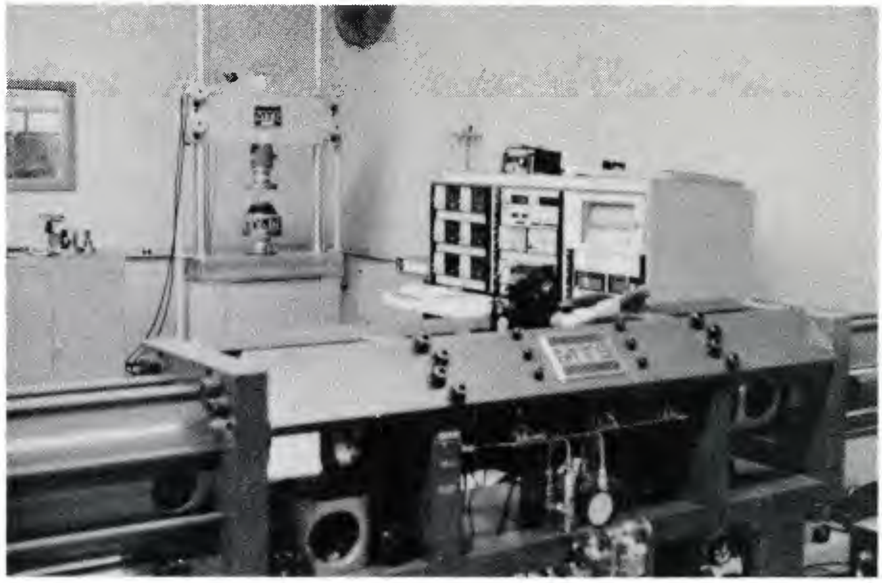
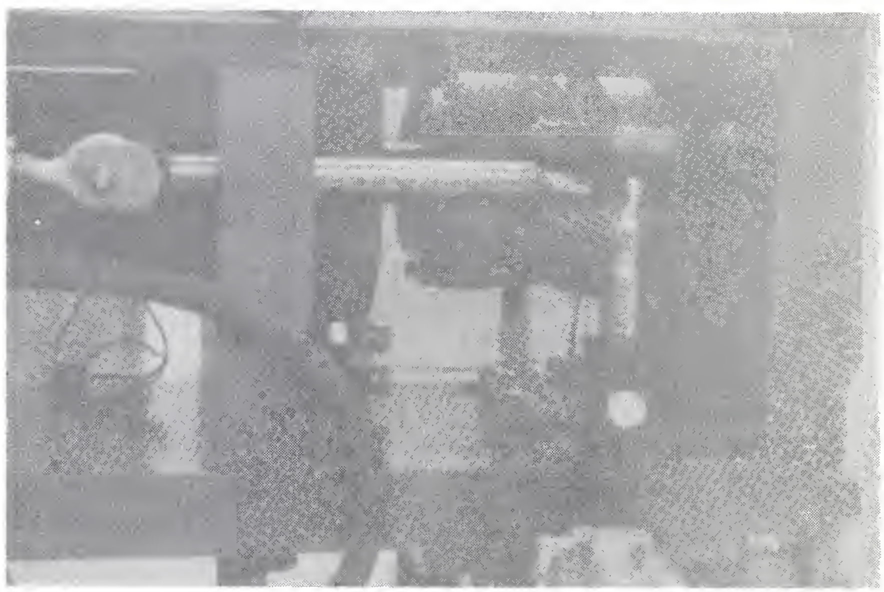


FIG. 8 THRUST BEARING FATIGUE TEST STAND

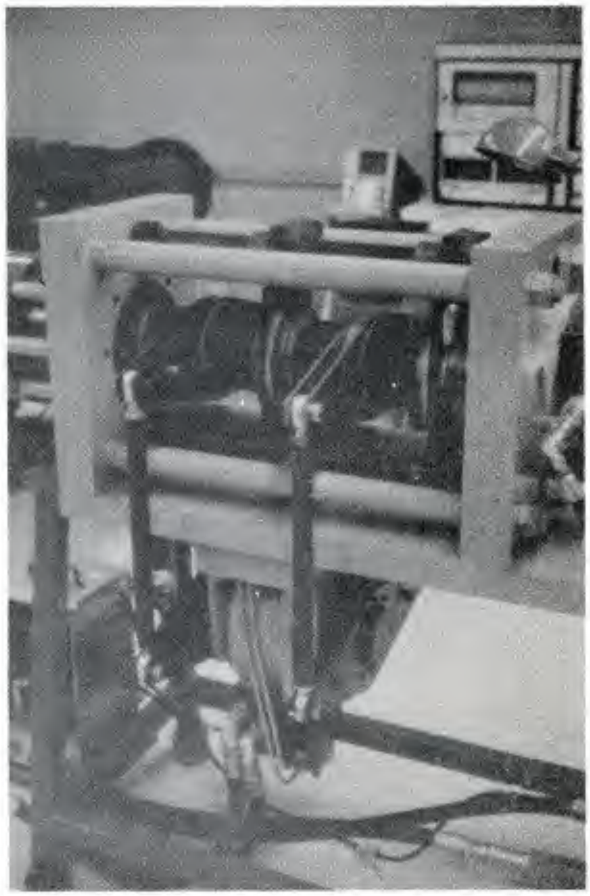




SPHERICAL BEARING

TEST RIG.

FIGURE 9



THRUST BEARING
TEST RIG.
FIGURE 10

TENTATIVE ENDURANCE SPECIMEN TEST PLAN

Test No.	Hours
1	2
2	3
3	5
4	10
5	20
6	30
7	50
8	100
9	200
10	300
11	500
12	1000
13	1500
	3720

NOTE: Loads for the first test will be estimates based on the results of the F.E.A. of this part. Loads for subsequent test will be chosen to obtain a good distribution of data.

Fig. 11.

SECTION 2.

METHODOLOGY OF FINITE ELEMENT ANALYSIS AT CR INDUSTRIES

This section will cover the mechanics of utilizing finite element analysis that are currently employed by CR Industries. The essential basis for our finite element program is Texgap controlled by E. B. Becker and R. S. Dunham at the University of Texas (see enclosed cover sheet for the program manual in Figure 1). The library elements used for our work are solid two-dimensional ring elements with the third displacement handled by one of the following rules; plane stress, plane strain, axial symmetry with no tangential displacement, axial symmetry with a constant tangential displacement and axial symmetry with tangential displacement following a sinusoidal distribution.

In order to have a meaningful solution with the above program, loading conditions must be restricted to those that are compatible with the chosen third dimension displacement condition. Plane strain and plane stress problems are normally well known. With the tangential displacement set to zero problems with axisymmetrical models and loading conditions are handled. Constant tangential displacement handles axial torsion on an axisymmetrical model. Sinusoidal tangential displacements are used to handle lateral loading cases and non-axial twisting or rotation on an axisymmetrical model. Unfortunately the complete set of boundary conditions chosen for each problem case must be

totally compatible with the displacement restriction used--combination types of loadings are not allowed in a single program run.

The most useful element for laminated elastomeric bearing work is the "Quad", which is a four node quadratic displacement solid ring element that can handle Poisson's ratio as close to ½ as desired. Also useful at times, is the "Tri" ring element, which is a three node quadratic displacement solid element that also allows Poisson's ratio to approach or equal ½. Other elements available are "Quad 8", "Liner", "Case" and "Crack".

The program has a good mesh generator for developing two-dimensional nodal points in both rectangular and polar co-ordinates. For some comlex problems, however, it has been found desirable to supplement the programs mesh generation with a pre-processing mesh generation program that feeds the main program. The program has a nice looping feature that aids in establishing connectivity, element assignment, material deployment and establishing boundary conditions. These features expedite the generation of the two-dimensional model that is needed for each problem solved by this finite element program. This model is supplied to the main program as an input data program.

The computation work for our finite element analysis is done on our IBM 370 computer located at Elgin, Illinois.

The operating system accepts card image programs supplied by a remote Tektronix 4051 terminal located at Elk Grove Village, Illinois. See Figure 2 for a sample input program. In processing a job the main computer pulls from storage a binary copy of the finite element program and produces a line printer file and a graphics data file. Both files are accessible at Elk Grove Village.

Finite element data is retained through line printing done at Elgin and graphics data plotted at Elk Grove Village. See Figure 3 for a sample element model plot. A sample of the output stress and strain, as line printed, is shown in Figure 4. The maximum and minimum stress and strains are calculated for each material. A sample of this summary is shown in Figure 5. Because of the tedium of reading 75 pages of computer line print, it is normal practice to plot the pertinent strain value from the line output with the graphics terminal. See Figure 6 for a sample strain plot.

Interreactive graphics can be used at CR Industries for model preparation. The part to be analysed is first drawn on the Tektronix 4051 CRT and into a data base by a CAD (Computer Aided Design) program (see Fig. 7 & 8). Auxililiary element model construction lines are added and the pertinent coordinate points are queried (see Fig. 9) for use in the input data program. After the input data program is assembled, it can

be read by our off-line preview program and a preview model generated (see Fig. 10, 11, 12 & 13). This debugging aid can save a considerable amount of mainframe time.

The following CR Industries capabilities result in a powerful elastomer bearing analysis tool:

A) A finite element program with solid elements for use with elastomeric material which have Poisson's ratios that approach ½.

B) Large main-frame computational capability.

C) Direct data input to a remote terminal.

D) Graphics output both to a CRT and hardcopy.

E) Interactive graphics input during model preparation.

F) Off-line verification of both the input data program and the element model.

G) Personnel skilled in modeling finite element problems and interpreting the resulting output.

TEXGAP–THE TEXAS GRAIN ANALYSIS PROGRAM

by R. S. Dunham *and* E. B. Becker

TICOM REPORT 73–1

Final Report
to the
United Technology Company
Sunnyvale, California
and
Air Force Rocket Propulsion Lab
Edwards, California

THE TEXAS INSTITUTE *for* COMPUTATIONAL MECHANICS
THE UNIVERSITY OF TEXAS AT AUSTIN
August, 1973

FIG. 1

```
$ ELASTOMERIC THRUST BEARING (TEST PROGRAM - MODEL 2)
SETUP,4
RUBBER,1,850,.5
STEEL,2,3E7,.3
TITANM,3,15E 6,.3
END,MATERIAL
1,1,3,2
1.5,2.5,2.5,1.5
0,0,.5,.5
1,2,3,7
1.5,2.5,2.5,1.5
.5,.5,.65,.65
1,7,3,8
1.5,2.5,2.5,1.5
.65,.65,1.15,1.15
END,GRID
ILOOP,2,1
QUAD,3,1,1
QUAD,1,1,2
QUAD,2,1,3
QUAD,1,1,4
QUAD,2,1,5
QUAD,1,1,6
QUAD,3,1,7
IEND
ILOOP,2,1
BC,SLOPE,1,1,1
BC,PRESSURE,1,7,3,7000
IEND
END,ELEMENTS
PLOT,ELEMENTS,1.25,-.5,2.75,1.5,10
AXISYM
STOP
```

FIG. 2

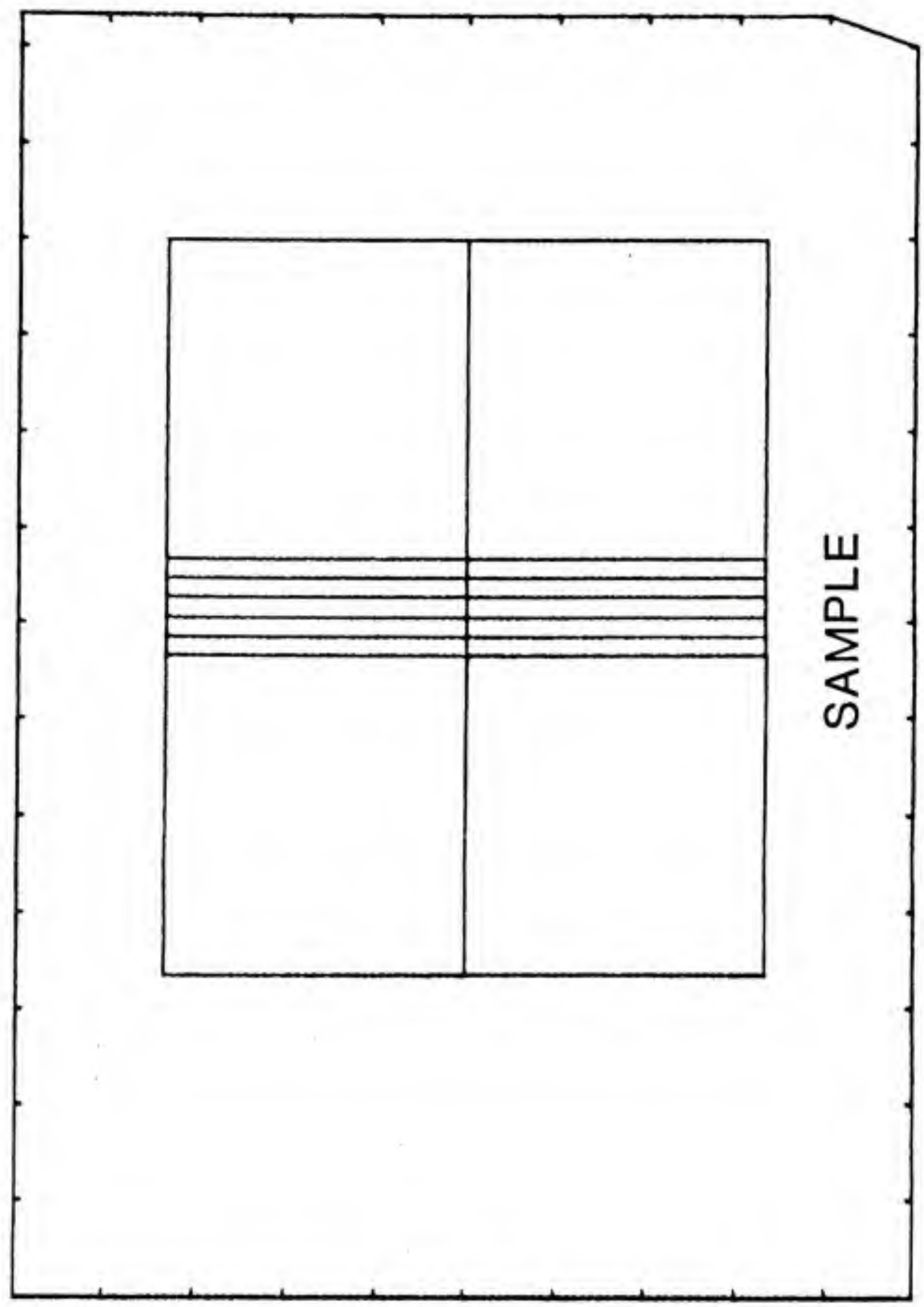


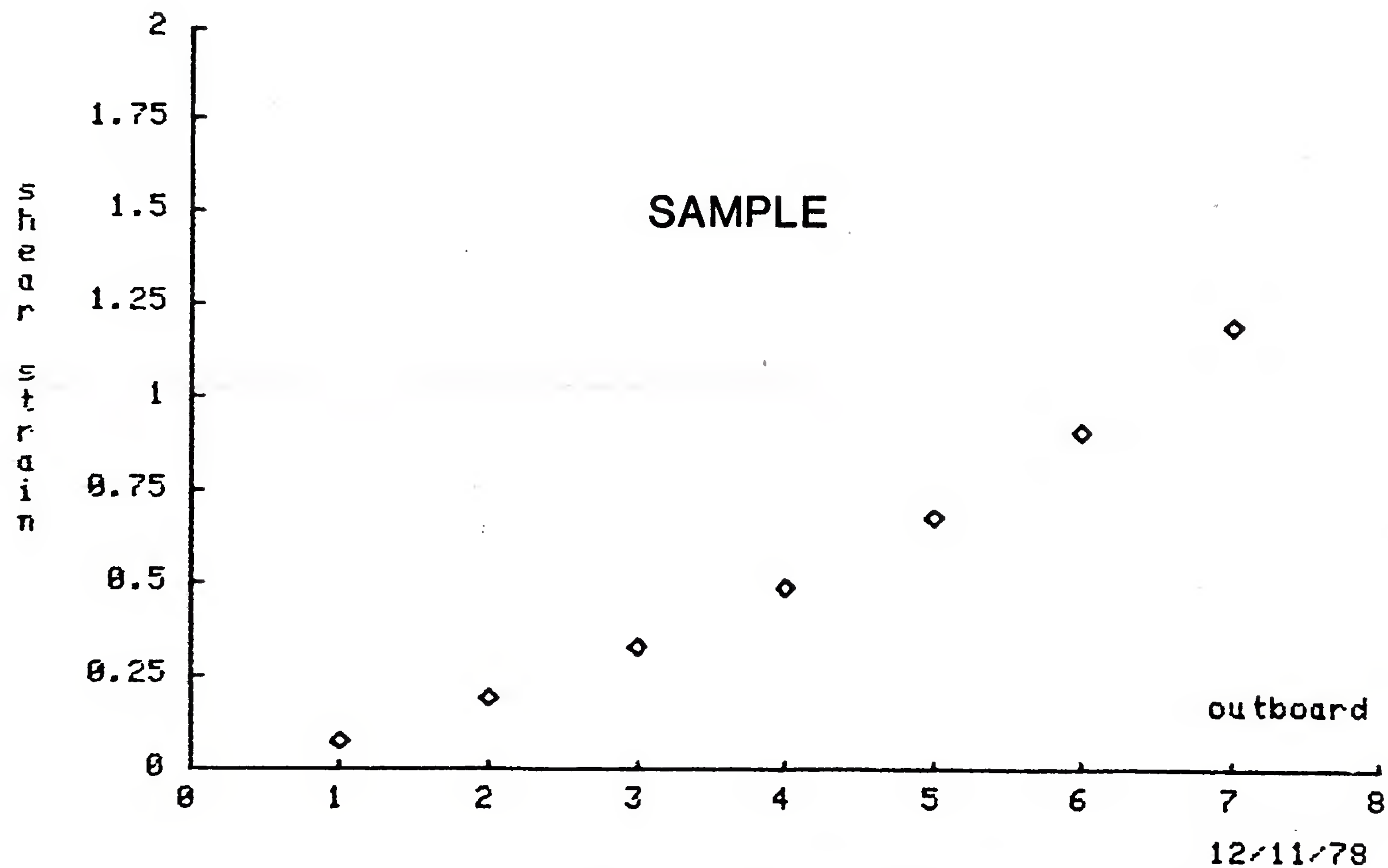
FIG. 3

```
DISPLACEMENTS FOR QUAD(LINER) NO     1

 I    J        RADIAL          AXIAL                  HOOP                  H
 1    1     0.2127D-03     -0.3512D-24      0.0                  -0.3010D-03
 2    1     0.3049D-03     -0.6972D-24      0.0                  -0.4416D-03
 2    2     0.2987D-03     -0.3319D-03      0.0                  -0.9962D-03
 1    2     0.2726D-03     -0.1229D-03      0.0                  -0.2856D-04
            0.2444D-03     -0.7432D-24      0.0
            0.3035D-03     -0.1565D-03      0.0
            0.2868D-03     -0.2453D-03      0.0
            0.2169D-03     -0.7851D-04      0.0

MIDSIDE STRESS AND STRAINS FOR QUAD(LINER) NO     1

SIDE    R        Z         TRR          TZZ          TOO          TRZ        TRO      TZO        MAX          MIN          TAUMAX
                           ERR          EZZ          EOO          ERZ        ERO      EZO

 1    1.7500   0.0      0.8435D 03  -0.7015D 04   0.3261D 03  -0.7182D 02   0.0      0.0     0.8441D 03  -0.7016D 04   0.3930D 04
                        0.1845D-03  -0.4966D-03   0.1397D-03  -0.1245D-04   0.0      0.0     0.1845D-03  -0.4966D-03   0.6812D-03
 2    2.0000   0.2500   0.5184D 03  -0.1015D 05  -0.7374D 03  -0.3023D 03   0.0      0.0     0.5269D 03  -0.1016D 05   0.5342D 04
                        0.2505D-03  -0.6638D-03   0.1518D-03  -0.5239D-04   0.0      0.0     0.2613D-03  -0.6646D-03   0.9259D-03
 3    1.7500   0.5000  -0.1169D 04  -0.6867D 04   0.1175D 03  -0.7181D 03   0.0      0.0    -0.1080D 04  -0.6956D 04   0.2938D 04
                        0.5236D-04  -0.4414D-03   0.1639D-03  -0.1245D-03   0.0      0.0     0.5008D-04  -0.4491D-03   0.5092D-03
 4    1.5000   0.2500  -0.9377D 02  -0.3403D 04   0.1098D 04  -0.3310D 03   0.0      0.0    -0.6103D 02  -0.3440D 04   0.1690D 04
                        0.4131D-04  -0.2459D-03   0.1446D-03  -0.5737D-04   0.0      0.0     0.4415D-04  -0.2487D-03   0.2929D-03

DISPLACEMENTS FOR QUAD(LINER) NO     2

 I    J        RADIAL          AXIAL                  HOOP                  H
 2    1     0.3049D-03     -0.6972D-24      0.0                  -0.4416D-03
 3    1     0.3384D-03     -0.3835D-24      0.0                  -0.2519D-03
 3    2     0.3299D-03     -0.1238D-03      0.0                  -0.7317D-04
 2    2     0.2987D-03     -0.3319D-03      0.0                  -0.9962D-03
            0.3618D-03     -0.7085D-24      0.0
            0.3831D-03     -0.7697D-04      0.0
            0.3131D-03     -0.2404D-03      0.0
            0.3035D-03     -0.1565D-03      0.0

MIDSIDE STRESS AND STRAINS FOR QUAD(LINER) NO     2

SIDE    R        Z         TRR          TZZ          TOO          TRZ        TRO      TZO        MAX          MIN          TAUMAX
                           ERR          EZZ          EOO          ERZ        ERO      EZO

 1    2.2500   0.0      0.7261D 03  -0.5822D 04   0.6550D 03   0.6872D 02   0.0      0.0     0.7267D 03  -0.6823D 04   0.3775D 04
                        0.1670D-03  -0.4872D-03   0.1608D-03   0.1191D-04   0.0      0.0     0.1670D-03  -0.4873D-03   0.6543D-03
 2    2.5000   0.2500  -0.8407D 02  -0.3420D 04   0.1206D 04   0.2803D 03   0.0      0.0    -0.6068D 02  -0.3444D 04   0.1692D 04
                        0.4148D-04  -0.2477D-03   0.1532D-03   0.4859D-04   0.0      0.0     0.4351D-04  -0.2497D-03   0.2932D-03
 3    2.2500   0.5000  -0.1131D 04  -0.6931D 04  -0.2450D 03   0.6718D 03   0.0      0.0    -0.1054D 04  -0.7008D 04   0.2977D 04
                        0.6239D-04  -0.4403D-03   0.1392D-03   0.1164D-03   0.0      0.0     0.6904D-04  -0.4470D-03   0.5160D-03
 4    2.0000   0.2500   0.5047D 03  -0.1015D 05  -0.7374D 03   0.2937D 03   0.0      0.0     0.5128D 03  -0.1016D 05   0.5334D 04
                        0.2594D-03  -0.6638D-03   0.1518D-03   0.5091D-04   0.0      0.0     0.2601D-03  -0.6645D-03   0.9246D-03
```

FIG. 4

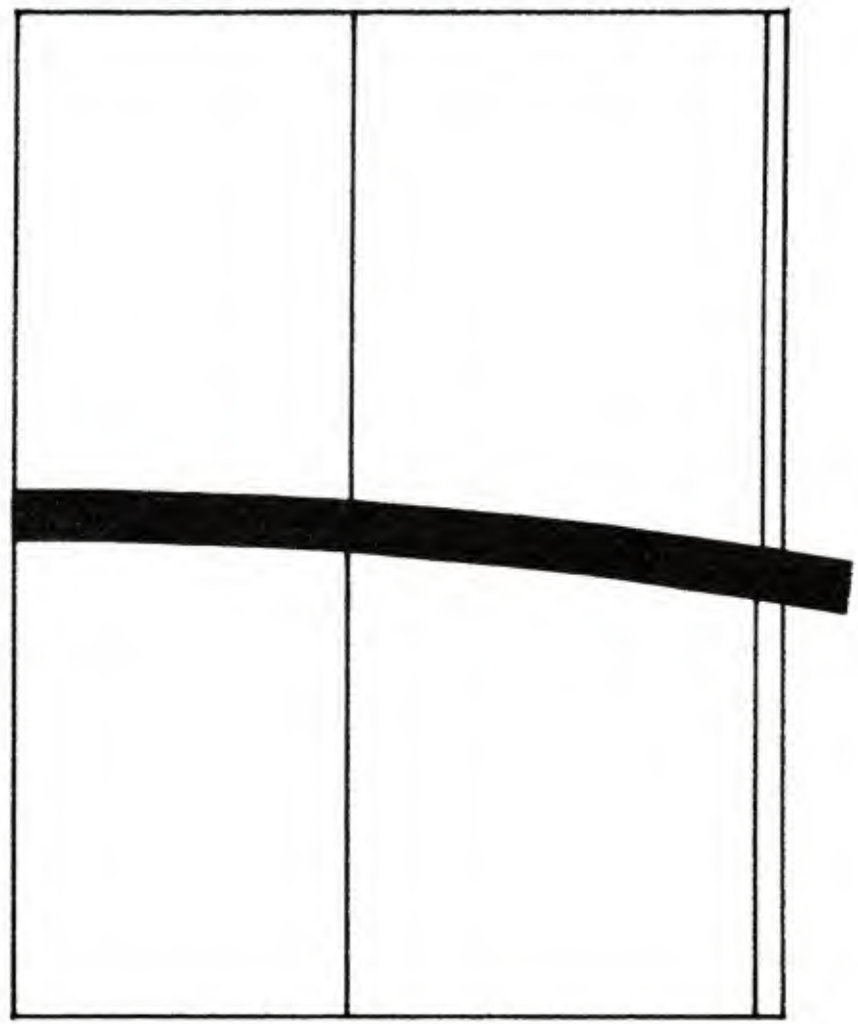
MATERIAL NO. 1	QUANTITY	R	Z	ELEM	MAXIMUM	R	Z	ELEM	MINIMUM
	RADIAL STRESS	1.500	0.575	7	-0.1415329D 04	2.000	0.575	8	-0.1232979D 05
	AXIAL STRESS	1.500	0.575	7	-0.1464780D 04	2.000	0.575	7	-0.1237981D 05
	HOOP STRESS	1.500	0.575	7	-0.1460910D 04	2.000	0.575	7	-0.1236688D 05
	TAURZ STRESS	1.750	0.530	3	0.3278019D 03	1.750	0.620	11	-0.3322344D 03
	TAURO STRESS	2.000	0.635	12	0.0	2.000	0.635	12	0.0
	TAUZO STRESS	2.000	0.635	12	0.0	2.000	0.635	12	0.0
	MAX STRESS	1.500	0.575	7	-0.1415322D 04	2.000	0.575	8	-0.1232979D 05
	MIN STRESS	1.500	0.575	7	-0.1464786D 04	2.000	0.575	8	-0.1237981D 05
	MAX SHEAR	1.750	0.620	11	0.3324266D 03	1.500	0.515	3	0.2448620D 02
	RADIAL STRAIN	2.500	0.635	12	0.8260673D-01	1.750	0.500	3	0.5235667D-04
	AXIAL STRAIN	1.500	0.635	11	-0.1697301D-01	2.250	0.620	12	-0.5434087D-01
	HOOP STRAIN	2.500	0.575	8	0.7841879D-02	1.500	0.635	11	-0.1160334D-01
	GAMRZ STRAIN	1.750	0.530	3	0.1156948D 01	1.750	0.620	11	-0.1172592D 01
	GAMRO STRAIN	2.000	0.635	12	0.0	2.000	0.635	12	0.0
	GAMZO STRAIN	2.000	0.635	12	0.0	2.000	0.635	12	0.0
	MAX STRAIN	1.750	0.620	11	0.5669476D 00	2.000	0.515	4	0.6557656D-01
	MIN STRAIN	1.500	0.515	3	-0.1732509D-01	2.250	0.650	12	-0.6066723D 00
	MAX SHEAR	1.750	0.620	11	0.1173270D 01	1.500	0.515	3	0.8642186D-01
MATERIAL NO. 2	QUANTITY	R	Z	ELEM	MAXIMUM	R	Z	ELEM	MINIMUM
	RADIAL STRESS	2.000	0.545	5	0.1250740D 05	2.500	0.605	10	0.1435560D 04
	AXIAL STRESS	1.500	0.545	5	-0.1527446D 04	2.000	0.545	6	-0.1236281D 05
	HOOP STRESS	2.250	0.620	10	0.7323177D 04	1.750	0.590	9	0.5844644D 04
	TAURZ STRESS	1.750	0.590	9	0.3333668D 03	1.750	0.560	5	-0.3300834D 03
	TAURO STRESS	2.000	0.605	10	0.0	2.000	0.605	10	0.0
	TAUZO STRESS	2.000	0.605	10	0.0	2.000	0.605	10	0.0
	MAX STRESS	2.000	0.545	5	0.1250742D 05	2.500	0.545	6	0.1435733D 04
	MIN STRESS	1.500	0.545	5	-0.1527556D 04	2.000	0.545	6	-0.1236284D 05
	MAX SHEAR	2.000	0.545	5	0.1243512D 05	2.500	0.545	6	0.1585767D 04
	RADIAL STRAIN	2.000	0.605	9	0.4751131D-03	2.500	0.545	6	-0.4326231D-05
	AXIAL STRAIN	1.500	0.605	9	-0.1321124D-03	2.000	0.545	6	-0.6040346D-03
	HOOP STRAIN	2.250	0.560	6	0.2459459D-03	1.750	0.590	9	0.1958407D-03
	GAMRZ STRAIN	1.750	0.590	9	0.2889179D-04	1.750	0.560	5	-0.2860723D-04
	GAMRO STRAIN	2.000	0.605	10	0.0	2.000	0.605	10	0.0
	GAMZO STRAIN	2.000	0.605	10	0.0	2.000	0.505	10	0.0
	MAX STRAIN	2.000	0.605	9	0.4751153D-03	2.500	0.545	6	-0.4321377D-05
	MIN STRAIN	1.500	0.605	9	-0.1321370D-03	2.000	0.545	6	-0.6040355D-03
	MAX SHEAR	2.000	0.545	5	0.1077711D-02	2.500	0.545	6	0.1374332D-03

FIG. 5



BOND LINE STRAIN FOR AMMRC SPECIMEN (MODEL 2)

FIG. 6



CAD DRAWING OF AMMRC FATIGUE TEST SPECIMEN

FIG. 7

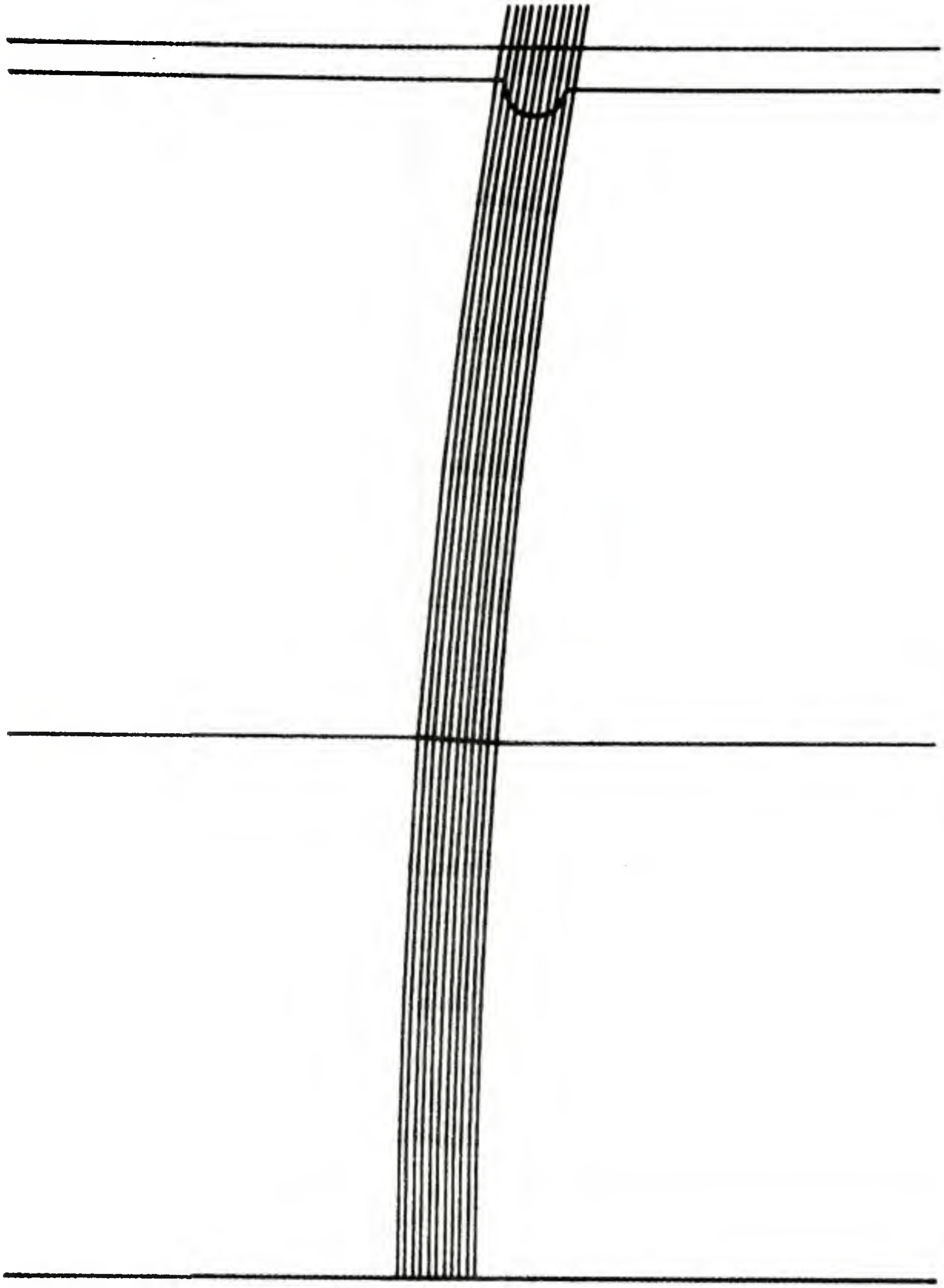
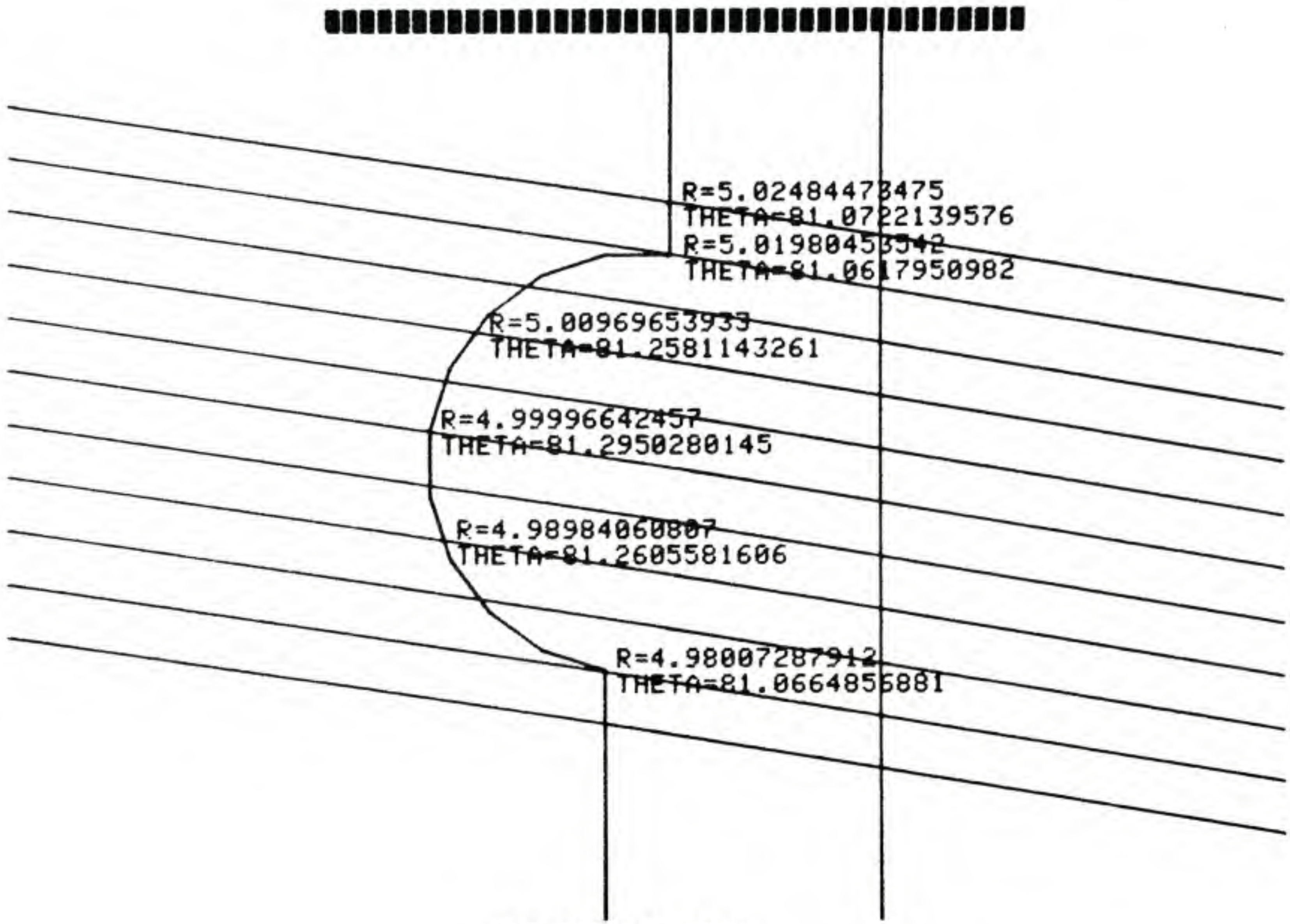


FIG. 8

BLOW UP OF FIG. 7



CAD QUERY LOCATION

FIG. 9

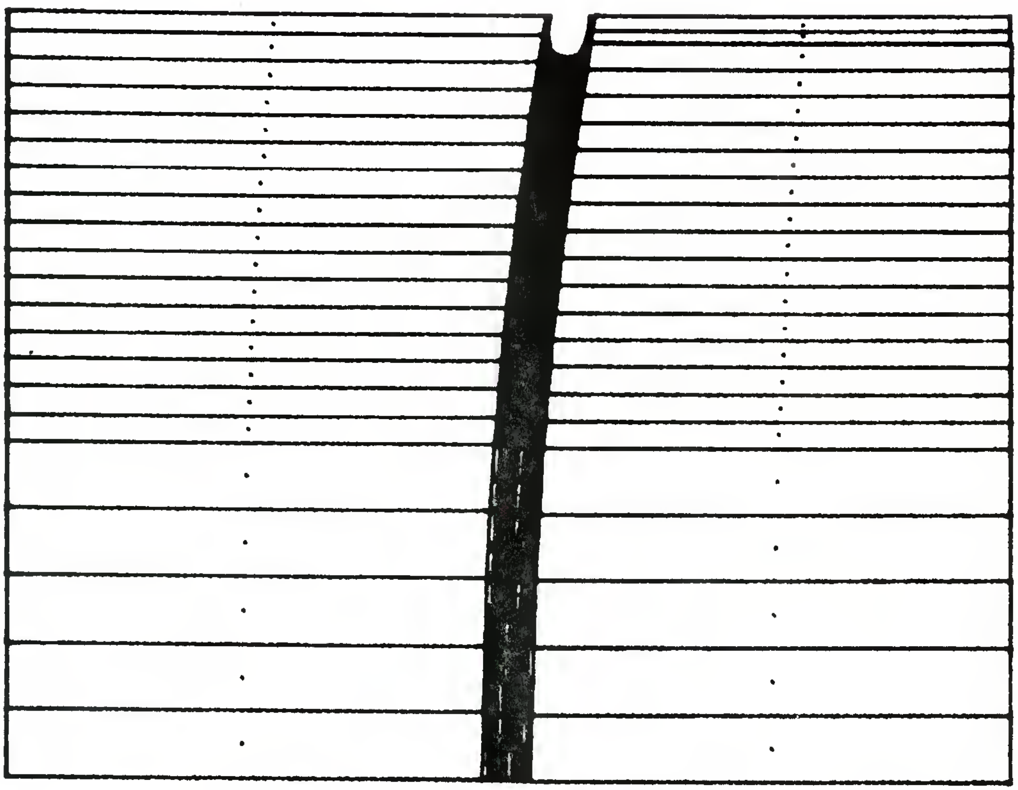
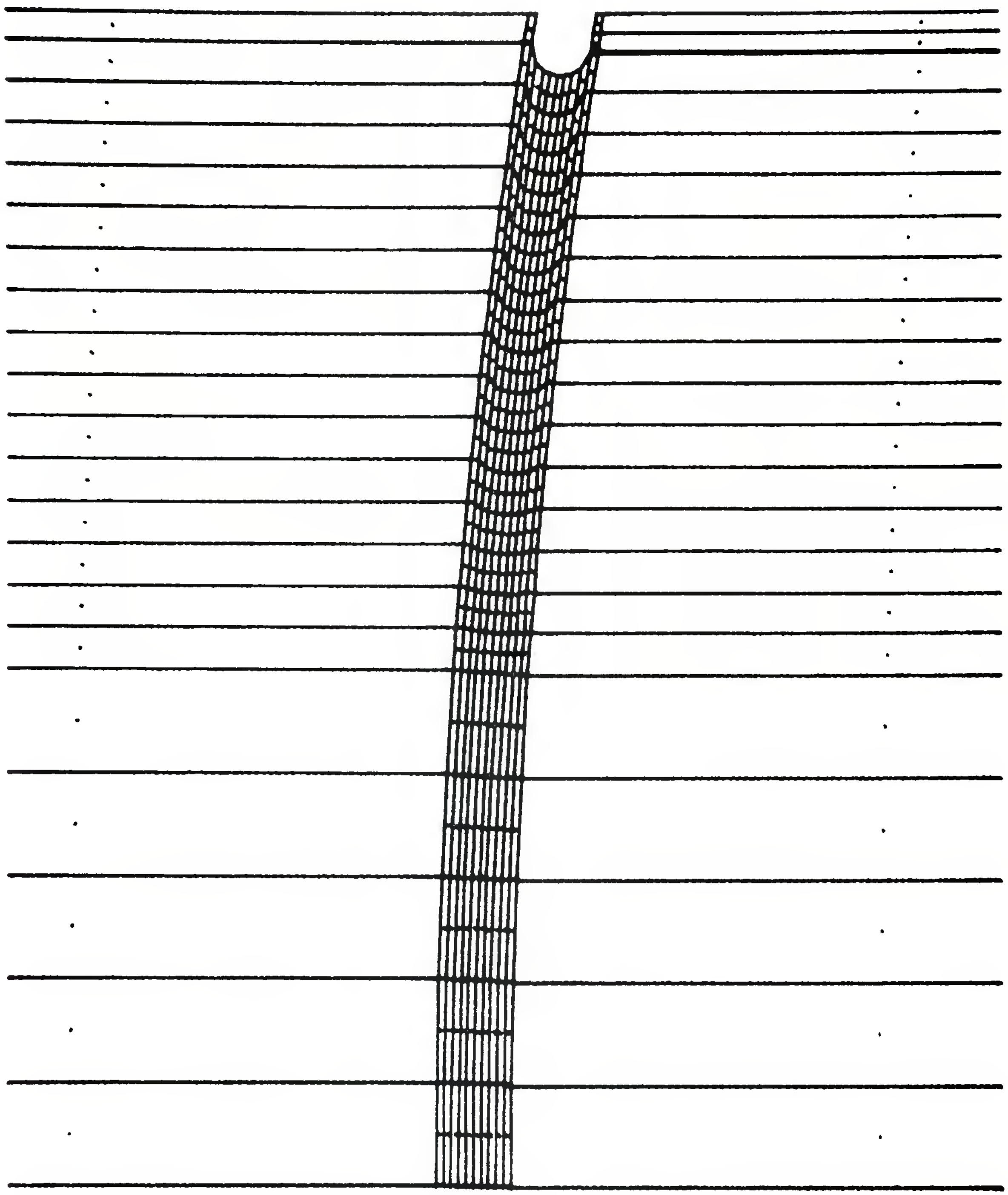


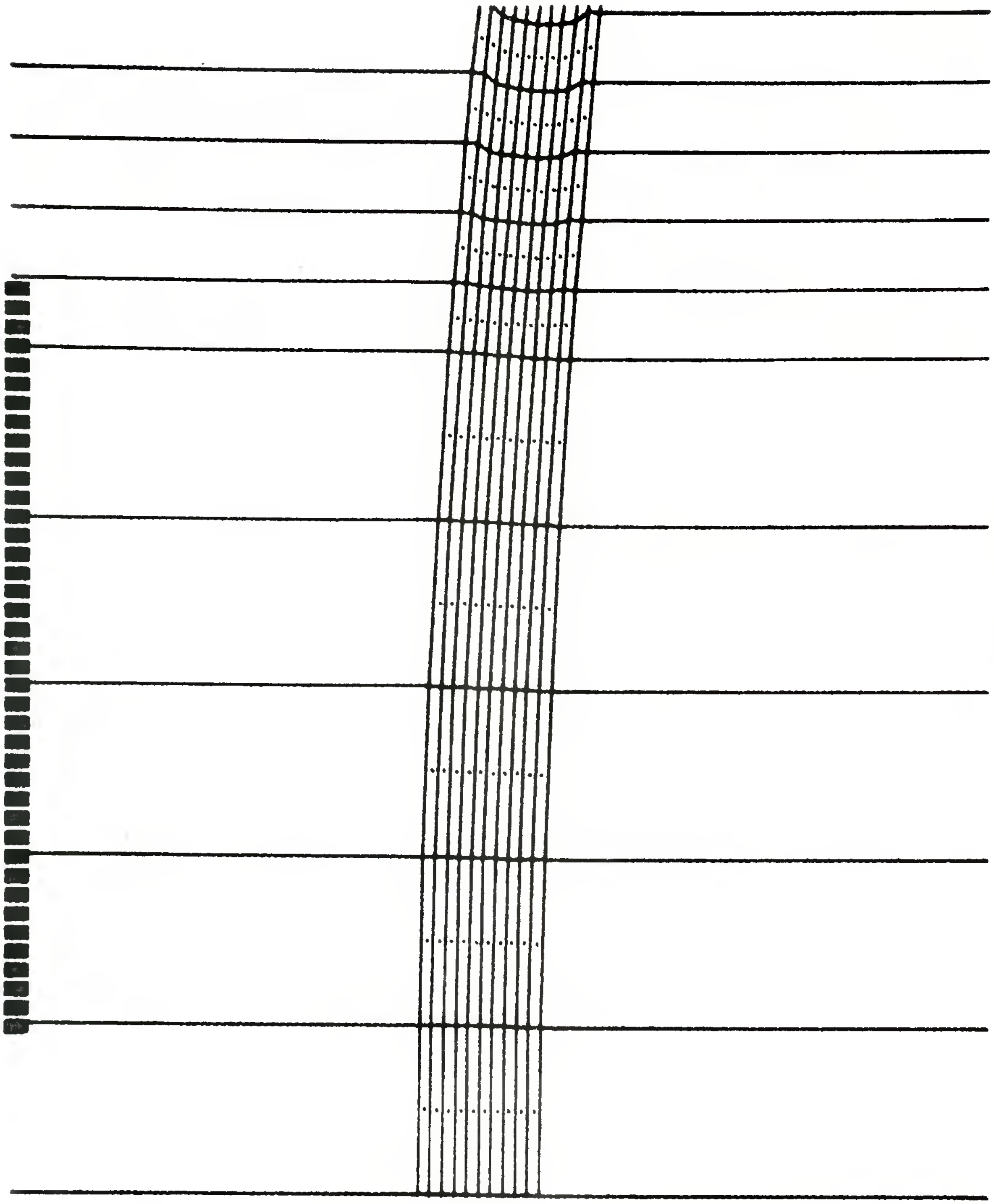
FIG. 10

PREVIEW MODEL OF AMMRC FATIGUE SPECIMEN



BLOW UP OF FIG. 10

FIG. 11



BLOW UP OF FIG. 10

FIG. 12

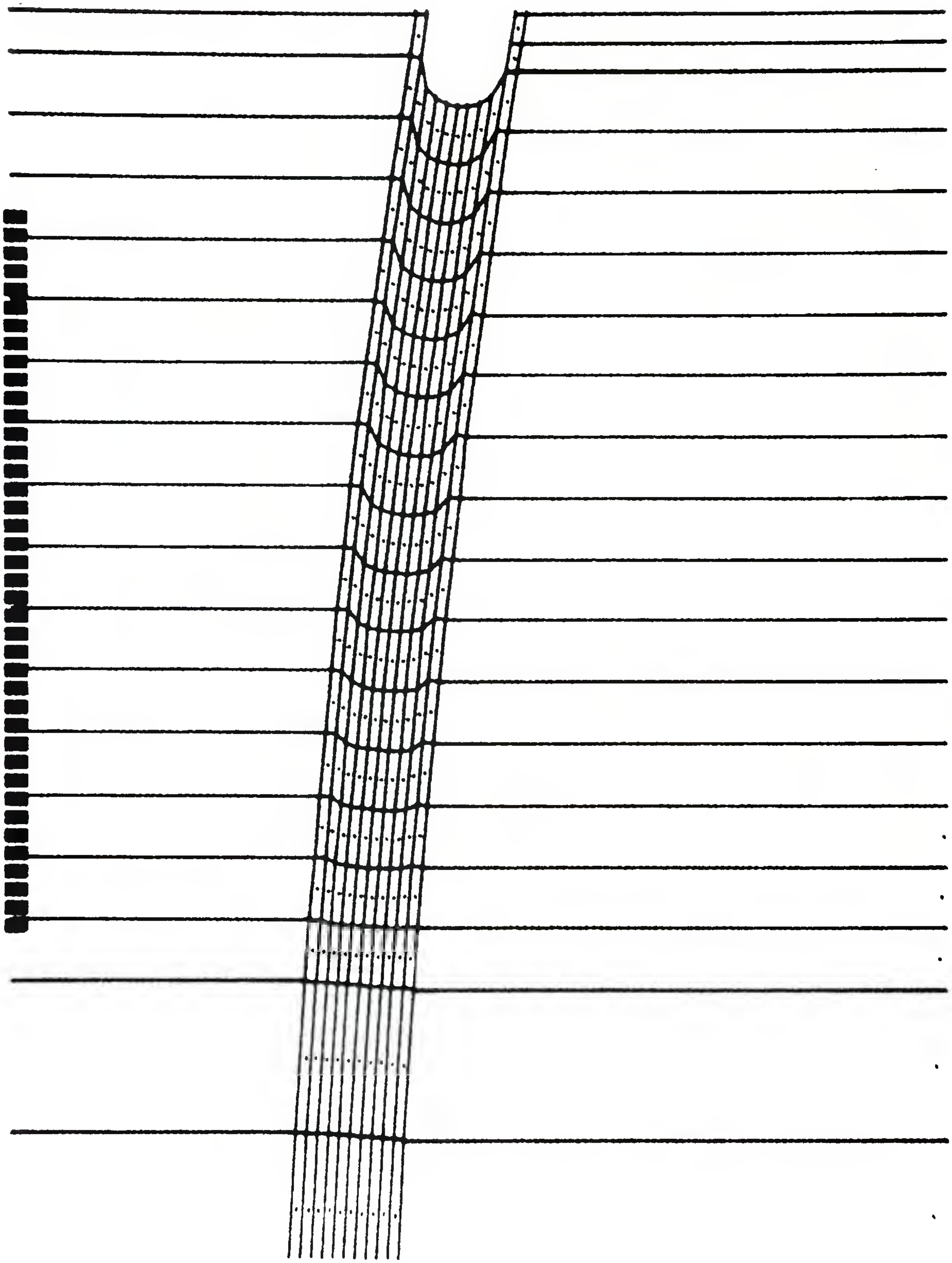


FIG. 13

BLOW UP OF FIG. 10

SECTION 3.

ANALYSIS OF ENDURANCE STRAINS

The previous section covered the use of the finite element method to determine stresses and strains within a laminated elastomeric bearing. It was explained how each loading case must be compatible with the tangential displacement specified for a single problem run. The result is that when all the individual loading cases shown in the S.E.S. Specification (see Section 1.) are analyzed, the analyst is left with a number of states of stress or strain at each location in the bearing. The task covered by this section is how to use this data to predict the life of the bearing.

The following discussion will show a method for determining the life of an elastomer when subject to a spectrum of non-random loading cases. For each loading case a finite element analysis will, in general, produce several shear strain resultants with similar and/or different geometric and time phase angles. The principal of superposition will be used to allow these resultants to be combined. The usual restriction on superposition of a linear stress-strain relationship, loading that is independent of deformation, etc., of course apply here. Fortunately for the elastomer in a laminated elastomeric bearing these conditions are usually met.

In October, 1968, C.H. Fagan, Senior R & D Engineer, Bell Helicopter, Fort Worth, Texas, published in the American Helicopter Society Periodical, a 5th power relationship

for the endurance life of natural rubber (see Figure 1). (Note, in this report γ will be used to represent the actual shear strain.) In order to find the combined effect of independent loading cases, Miner's Rule will be used. See Appendix I for the specialized case of using Miner's Rule on materials that have a 5th power endurance life relationship. Effective values for the pertinent parameters from the Blackhawk load and motion spectrum (S.E.S.) were calculated and are given in Figure 2.

The analysis of the state of stress and strain for an elastomer is very different from what it would be for most common engineering materials. The strains are usually so large that the analytical basis for small strain analysis is unjustifiable. For relatively incompressible elastomeric materials (Poisson's ratio close to ½) conventional normal stress-strain relationships do not hold up. Shear stress, however, is still directly related to shear strain even for strains that would in other material be past the yield point. When converting from a strain analysis to a stress analysis a troublesome hydrostatic pressure term must be found. In the case of thin elastomer and metal laminates this hydrostatic pressure term can be large. Normally a vibratory hydrostatic stress in-and-of itself does not result in fatigue damage in an elastomeric part. It has been found that some of the best correlations between

experimental and analytical results for elastomers have been based on shear strain (see Figure 1).

One of the problems that an analyst faces in analyzing complex elastomeric bearings is that the state of strain is seldom one-dimensional but, usually two- or three-dimensional. The reason that this poses such a large problem for the analyst is that two- and three-dimensional shear failure theories do not exist for elastomers. The analyst is, therefore, sometimes more interested in finding an "effective" one-dimensional state of strain than he is in obtaining a complete two- or three-dimensional solution to a problem.

It would be thought that the best way to combine states of strain for a superposition solution to a problem would be a tensor addition (See Appendix II). At this point in time, however, this is not necessarily the case. The lack of a two- or three-dimensional endurance failure theory makes it difficult to use tensor results to predict the endurance life of elastomeric parts. Classical solutions to elastomeric bearing problems are normally given in terms of a maximum shear strain and superpositions is made by vector methods. It is easier to visualize the interaction of individual states of strains by looking at their maximum shear strains rather than their tensors.

Shear strains are often combined by vector methods. Shear strains are normally identified by the plane around whose normal line they act. For the case of combining shear strains with coincident normal lines the reader is referred to classical two-dimensional strain analysis for a discussion of Mohr's cirlce which looks like a "double angle vector". This technique will not be needed for this study. For the case of combining shear strains with noncoincident normal lines, see Figure 3 for the mathematics of combining time dependent vectors. Appendix II shows that for certain important cases the behavior of the strain tensor is the same as a conventional vector.

Normally an analytical analysis of elastomer degradation in an elastomeric bearing is valid only until endurance damage has resulted. After endurance damage the original model used in the analysis is no longer valid. The degradation of the elastomer in an elastomeric bearing has been found to be progressive and noncatastrophic. Actual bearing life is characteristically several times the calculated and observed life to first damage.

It might be thought that because of the larger amount of data that is available on metal fatigue, that the analysis of the endurance life of the metal shells would be less difficult. Determining the stress in the shell of the Blackhawk main

rotor thrust bearing is relatively straight forward but the resulting endurance "S-N" is usually at the low cycle end of the endurance curve making a precise life prediction very difficult. For the Blackhawk main rotor spherical bearing the maximum shell stress results from a combined loading case that has a shifting loading vector. This prevents the use of superposition and a full three-dimensional finite element analysis would be needed.

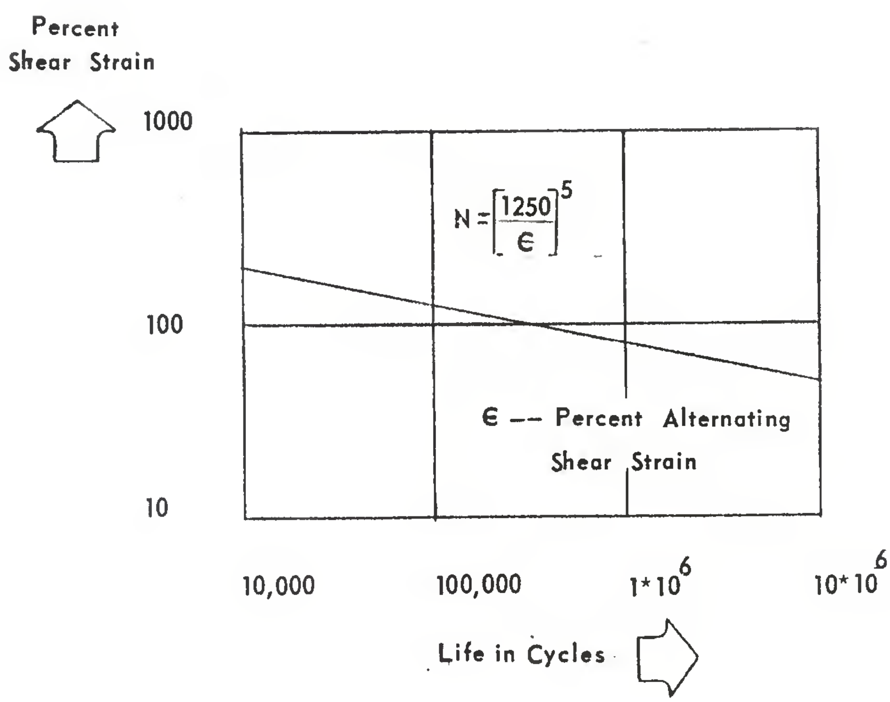

Percent
Shear Strain
1000
100
10
$N = \left[\frac{1250}{\epsilon}\right]^5$
ϵ -- Percent Alternating
Shear Strain
10,000
100,000
$1*10^6$
$10*10^6$
Life in Cycles

Fig. 1.

EFFECTIVE MAGNITUDES AND PHASE

ANGLES FOR THE S.E.S. SPECTRUM

Vibratory pitch change ($\pm\ \Theta_z$) --------$\pm 6.54^{\circ}$ @ 0°

Flap ($\pm\Theta_x$)----------------------------$\pm 3.58^{\circ}$ @ 90°

Lead-lag ($\pm\ \Theta_y$)-----------------------$\pm 1.5^{\circ}$ @ 90°

Vibratory centrifugal load------------± 315 lbs. @ 90°

Vibratory out-of-plane load-----------$\pm 1{,}292$ lbs. @ 90°

Normal centrifugal load---------------68,000 lbs.

Over-speed centrifugal load-----------82,000 lbs.

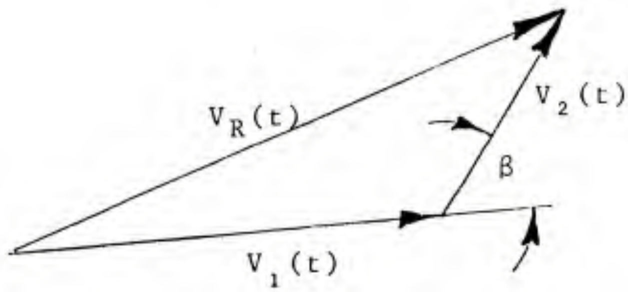
Note 1: The first 5 @ 258 cycles per second

Note 2: The first 5 effective magnitudes were obtained from the S.E.S. with the following formula from the Appendix I

$$\Theta_e = \sqrt[5]{\frac{\sum_{i=1}^{m} N_i (\Theta_i)^5}{\sum_{i=1}^{m} N_i}}$$

FIG. 2.

COMBINATION OF TIME DEPENDENT VECTORS



$$V_1(t) = ||V_1||\,SIN\omega t$$

$$V_2(t) = ||V_2||\,SIN(\omega t + \theta)$$

Where $||V||$ is the maximum value of the vector V.

$$V_R(t) = \pm\sqrt{\left[||V_1||\,SIN\omega t\right]^2 + \left[||V_2||\,SIN(\omega t + \theta)\right]^2 + 2||V_1||*||V_2||\,SIN\omega t\,SIN(\omega t + \theta)\,COS\beta}$$

PHASE ANGLE θ	VECTOR ANGLE β	MAXIMUM MAGNITUDE $\|\|V_R\|\|$
0	0	$\|\|V_1\|\| + \|\|V_2\|\|$
0	$\pm 90^o$	$\sqrt{\|\|V_1\|\|^2 + \|\|V_2\|\|^2}$
$\pm 90^o$	0	$\sqrt{\|\|V_1\|\|^2 + \|\|V_2\|\|^2}$
$\pm 90^o$	$\pm 90^o$	Greater of* $\|\|V_1\|\|$ or $\|\|V_2\|\|$
0	180^o	$\Big\|\, \|\|V_2\|\| - \|\|V_1\|\| \,\Big\|$
180^o	0	$\Big\|\, \|\|V_2\|\| - \|\|V_1\|\| \,\Big\|$

*It is customary in elastomeric strain analysis to also consider the Miner's Rule effect of the smaller vector.

Fig. 3

A P P E N D I X I

PROCEDURE FOR CALCULATING THE ENDURANCE LIFE OF ELASTOMERS

The following procedure is intended for materials that follow the fifth power life rule (see the body of this report). It is specialized to incorporate Miner's rule for the accumulated latent damage that results from a spectrum of loading conditions.

The fifth power life rule is

$$N = \left(\frac{12.5}{\gamma}\right)^5$$

Where:

γ = Is the shear strain.

N -- Is the life in cycles.

Miner's rule states that apparent damage occurs when

$$\sum_{i=1}^{m} \frac{N_i}{N_f} = 1$$

Where:

N_i -- Is the number of cycles at the i'th loading case.

N_f -- Is the number of cycles to apparent damage at

the i'th load.

m -- Is the total number of loading cases in the loading spectrum.

The life of an elastomeric part to first apparent damage then is

$$\text{Life (hours)} = \frac{1}{\sum_{i=1}^{m} \frac{N_i}{\left(\frac{12.5}{\gamma_i}\right)^5}}$$

$$\text{Life} = \frac{(12.5)^5}{\sum_{i=1}^{m} N_i \, (\gamma_i)^5}$$

Where:

N_i -- Is now the number of loading cycles per hour for the i'th case.

To simplify calculations when a spectrum of strain conditions is given, a single strain can be found that is equivalent to the spectrum in that it will produce a damage equivalent to the spectrum when applied for the same total number of cycles. This equivalent value may be found as follows:

$$\gamma_e = \sqrt[5]{\frac{\sum_{i=1}^{m} N_i \, (\gamma_i)^5}{\sum_{i=1}^{m} N_i}}$$

Where:

γ_e -- Is effective strain magnitude.

Obviously for materials with a linear stress-strain relationship an equivalent value may be found by this procedure for any load or motion that is specified by a spectrum of conditions.

A P P E N D I X II

COMBINATION OF STRAINS BY THE STRAIN TENSOR METHOD

The three - dimensional strain tensor is

$$\begin{bmatrix} \varepsilon_x & \tfrac{1}{2}\gamma_{xy} & \tfrac{1}{2}\gamma_{xz} \\ \tfrac{1}{2}\gamma_{xy} & \varepsilon_y & \tfrac{1}{2}\gamma_{yz} \\ \tfrac{1}{2}\gamma_{xz} & \tfrac{1}{2}\gamma_{yz} & \varepsilon_z \end{bmatrix}$$

where ε_x, ε_y & ε_z are the normal strains along the X, Y & Z axes respectively

and γ_{xy}, γ_{yz} & γ_{xz} are the shear strains acting on X-Y, Y-Z, X-Z planes respectively.

In order to solve for the principal strains and maximum shear strains the following eigenmatrix is used;

$$\begin{bmatrix} (\varepsilon_x - P) & \tfrac{1}{2}\gamma_{xy} & \tfrac{1}{2}\gamma_{xz} \\ \tfrac{1}{2}\gamma_{xy} & (\varepsilon_y - P) & \tfrac{1}{2}\gamma_{yz} \\ \tfrac{1}{2}\gamma_{xz} & \tfrac{1}{2}\gamma_{yz} & (\varepsilon_z - P) \end{bmatrix} = 0$$

where P is a principal strain.

This matrix equation results in the following cubic equation in terms of strain invarients;

$$P^3 - I_1 P^2 + I_2 P - I_3 = 0$$

where
$$I_1 = (\varepsilon_x + \varepsilon_y + \varepsilon_z)$$
$$I_2 = (\varepsilon_x\varepsilon_y + \varepsilon_y\varepsilon_z + \varepsilon_z\varepsilon_x) - \tfrac{1}{4}(\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{xz}^2)$$
$$I_3 = \varepsilon_x\varepsilon_y\varepsilon_z + \tfrac{1}{4}(\gamma_{xy}\gamma_{yz}\gamma_{xz} - \varepsilon_x\gamma_{yz}^2 - \varepsilon_y\gamma_{xz}^2 - \varepsilon_z\gamma_{xy}^2)$$

The maximum shear strains are

$$\gamma_1 = ABS(P_1 - P_2);\ \gamma_2 = ABS(P_2 - P_3);\ \gamma_3 = ABS(P_3 - P_1)$$

where P_1, P_2 & P_3 are the principal strains (roots of the cubic).

A computer program in Basic to solve these equations is shown in Figure 1. Figure 2. shows some interesting maximum shear strain results for monoplanar, biplanar and triplanar states of shear.

NOTE: The 2nd, 4th, 5th and 6th examples have a maximum shear strain resulting from a biplanar state of shear strain that is equal to the vector combination of the shear strains. The 3rd example shows that this result can not be expanded to the triplanar case.

As an example the maximum shear strain will be calculated for the fourth layer of the spearical bearing at the I.D. for 6 and 12 o'clock positions.

The flap strain tensor is

$$3.58* \begin{bmatrix} .03400 & -.03205 & -.03518 \\ -.03205 & -.03988 & -.05858 \\ -.03518 & -.05858 & 0 \end{bmatrix}$$

The vibratory in-plane strain tensor is

$$(-1)* \frac{315}{68000}* \begin{bmatrix} -1.314 & -1.358 & 0 \\ -1.358 & 1.343 & 0 \\ 0 & 0 & .0003 \end{bmatrix}$$

The vibratory out-of-plane strain tensor is

$$\begin{bmatrix} -.03417 & -.03521 & .0023 \\ -.03521 & .03509 & .0038 \\ .0023 & .0038 & 0 \end{bmatrix}$$

The combined strain tensor is

$$= \begin{bmatrix} .1217 & .1390 & -.1317 \\ .1390 & -.0870 & -.2163 \\ -.1317 & -.2163 & 0 \end{bmatrix}$$

The principal strains and maximum shear strains resulting from this strain tensor is calculated in Figure 3.

Great care must be excercised with regard to the choice of signs of the tensors since an incorrect sign will completely alter the boundary conditions of the problem.

At this point we must take a large and as of yet unjustified step in using the triplanar maximum as the uniplanar value. The maximum strain of .38001 shown in Figure 3 (triplanar) compares to .379 obtained by vector combination of these states of strain as shown below:

The two-dimensional maximum shear strain from the above tensors are,

$$\gamma_{\text{flap}} = \sqrt{(.03400 - (-.03988))^2 + (-.03205)^2} = .0803$$

$$\gamma_{\text{vibratory in - plane}}$$

$$= \sqrt{(-1.314 - 1.343)^2 + (-1.358)^2} = 2.9839$$

γ vibratory out-of-plane

$$= \sqrt{(-.03417 - .03509)^2 + (-.03521)^2} = .07769$$

The resulting combined shear strain is

$$\gamma_{v1} = 3.58 * .0803 + 2.9839 \left(\frac{315}{68000}\right) + .07769$$

$$= .379$$

```
100 PRINT "LIJPRINICPAL STRAIN DETERMINATIONJ"
110 PRINT "ENTER EPSILON - X ";
120 INPUT X
130 PRINT "ENTER EPSILON - Y ";
140 INPUT Y
150 PRINT "ENTER EPSILON - THETA ";
160 INPUT T
170 PRINT "ENTER GAMMA --- XY ";
180 INPUT T0
190 PRINT "ENTER GAMMA --- XTHETA ";
200 INPUT Y0
210 PRINT "ENTER GAMMA --- YTHETA ";
220 INPUT X0
230 I1=-(Y+X+T)
240 I2=X*Y+X*T+Y*T-(T0↑2+X0↑2+Y0↑2)/4
250 I3=-(X*Y*T+(T0*X0*Y0-X*X0↑2-Y*Y0↑2-T*T0↑2)/4)
260 S=0.3
270 R=((S+I1)*S+I2)*S+I3
280 R1=(3*S+2*I1)*S+I2
290 H=S
300 ON SIZE THEN 330
310 S=S-R/R1
320 IF ABS(R/(H*R1))>1.0E-12 THEN 270
330 B=I1+S
340 C=(S+I1)*S+I2
350 D=B*B/4-C
360 IF D<-1.0E-3 THEN 450
370 ON SIZE THEN 390
380 D=SQR(D)
390 S1=-B/2-D
400 S2=-B/2+D
410 PRINT "PRINCIPAL STRAINS _",S,S1,S2
420 PRINT "MAXIMUM SHEAR STRAINS "
430 PRINT ABS(S-S1),ABS(S1-S2),ABS(S2-S),"J"
```

FIG. 1

```
440 GO TO 110
450 PRINT "IMPOSSIBLE STATE OF STRAIN J"
460 GO TO 110
470 END
```

FIG. 1 (CONTINUED)

PRINICPAL STRAIN DETERMINATION

```
ENTER EPSILON - X 0
ENTER EPSILON - Y 0
ENTER EPSILON - THETA 0
ENTER GAMMA --- XY 1
ENTER GAMMA --- XTHETA 0
ENTER GAMMA --- YTHETA 0
PRINCIPAL STRAINS
 0.5              -0.5              0
MAXIMUM SHEAR STRAINS
 1                 0.5              0.5
```

EXAMPLE 1

```
ENTER EPSILON - X 0
ENTER EPSILON - Y 0
ENTER EPSILON - THETA 0
ENTER GAMMA --- XY 1
ENTER GAMMA --- XTHETA 1
ENTER GAMMA --- YTHETA 0
PRINCIPAL STRAINS
 0                -0.707106781187   0.707106781187
MAXIMUM SHEAR STRAINS
 0.707106781187    1.41421356237   0.707106781187
```

EXAMPLE 2

$\sqrt{1^2+1^2} = 1.41421356$

```
ENTER EPSILON - X 0
ENTER EPSILON - Y 0
ENTER EPSILON - THETA 0
ENTER GAMMA --- XY 1
ENTER GAMMA --- XTHETA 1
ENTER GAMMA --- YTHETA 1
PRINCIPAL STRAINS
 -0.499999982831   -0.500000017169   1
MAXIMUM SHEAR STRAINS
 3.433705587E-8     1.50000001717    1.49999998283
```

EXAMPLE 3

$\sqrt{1^2+1^2+1^2} = 1.7320508$

FIG. 2

PRINICPAL STRAIN DETERMINATION

```
ENTER EPSILON - X 0
ENTER EPSILON - Y 0
ENTER EPSILON - THETA 0
ENTER GAMMA --- XY 0
ENTER GAMMA --- XTHETA 1
ENTER GAMMA --- YTHETA 2
PRINCIPAL STRAINS
 0                 -1.11803398875     1.11803398875
MAXIMUM SHEAR STRAINS
 1.11803398875      2.2360679775      1.11803398875
```

EXAMPLE 4

$\sqrt{1^2+2^2} = 2.2360679$

```
ENTER EPSILON - X 1
ENTER EPSILON - Y 1
ENTER EPSILON - THETA 1
ENTER GAMMA --- XY 1
ENTER GAMMA --- XTHETA 2
ENTER GAMMA --- YTHETA 0
PRINCIPAL STRAINS
 -0.11803398875     1                 2.11803398875
MAXIMUM SHEAR STRAINS
 1.11803398875      1.11803398875     2.2360679775
```

EXAMPLE 5

$\sqrt{1^2+2^2} = 2.2360679$

```
ENTER EPSILON - X 1
ENTER EPSILON - Y 1
ENTER EPSILON - THETA 1
ENTER GAMMA --- XY -1
ENTER GAMMA --- XTHETA 1
ENTER GAMMA --- YTHETA 0
PRINCIPAL STRAINS
 0.292893218813     1                 1.70710678119
MAXIMUM SHEAR STRAINS
 0.707106781187     0.707106781187    1.4142135623
```

EXAMPLE 6

$\sqrt{(-1)^2 + 1^2} = 1.41421356$

FIG. 2 (CONTINUED)

```
PRINCIPAL STRAIN DETERMINATION

ENTER EPSILON - X .09364
ENTER EPSILON - Y -.18408
ENTER EPSILON - THETA 0
ENTER GAMMA --- XY -.14366
ENTER GAMMA --- XTHETA -.12364
ENTER GAMMA --- YTHETA -.20592
PRINCIPAL STRAINS
 0.125984476751    -0.254030749459   0.0376062727086
MAXIMUM SHEAR STRAINS
 0.38001522621     0.291637022168    0.088378204042
```

FIG. 3

SECTION 4.

ANALYSIS OF THE AMMRC FATIGUE SPECIMEN

A fatigue specimen has been designed (see 80 6627 in Figure 1). It was designed with an undercut radius at the O.D. of the part that is intended to lower the strain at this critical location. This is normal design practice. The location of this radius is shown in the enlarged section of Fig. 1. Note, the spherical design of the elastomer will minimize the effects of equipment nonparallelism during endurance testing.

A fine mesh model for this specimen was generated and is shown in Figure 2. Note, this model has a small center hole (not obvious) that avoids a mathematical pole in the analysis and is eliminated by the boundary conditions applied to the model. A finite element analysis (F.E.A.) was completed on this model. For this analysis the model was loaded with a compressive force system equal to the half amplitude range to be applied during the fatigue tests. A listing of the input data program is included in Appendix I. The shear strain occurring along the bond line is shown in Figure 3. The location of this bond line strain is shown on the model in Figure 2 as line A-A. The strain along the undercut radius is shown in Figure 4. The location of this radius is shown again on the model in Figure 2 along Curve A-B-C.

Figure 5 is the second model of the fatigue test spec-

imen. This coarse model was set up with the thickness of the elastomer layer represented by a single element. The elastomer layer is divided so that each of seven elements have the same polar angle width. The bond line shear strain is shown in Figure 6. The program for this analysis is given in Appendix II.

The third model as shown in Figure 7 incorporates a small element at the outside edge to improve the resolution of strain at this critical position. The reasoning behind this procedure is that this finite element analysis program actually only calculates the state of strain at an integration point in the middle of each side. The aim is to get a reading from a "mid-side mode" near the edge of the part. The strain results for this model are given in Figure 8. The program is listed in Appendix III.

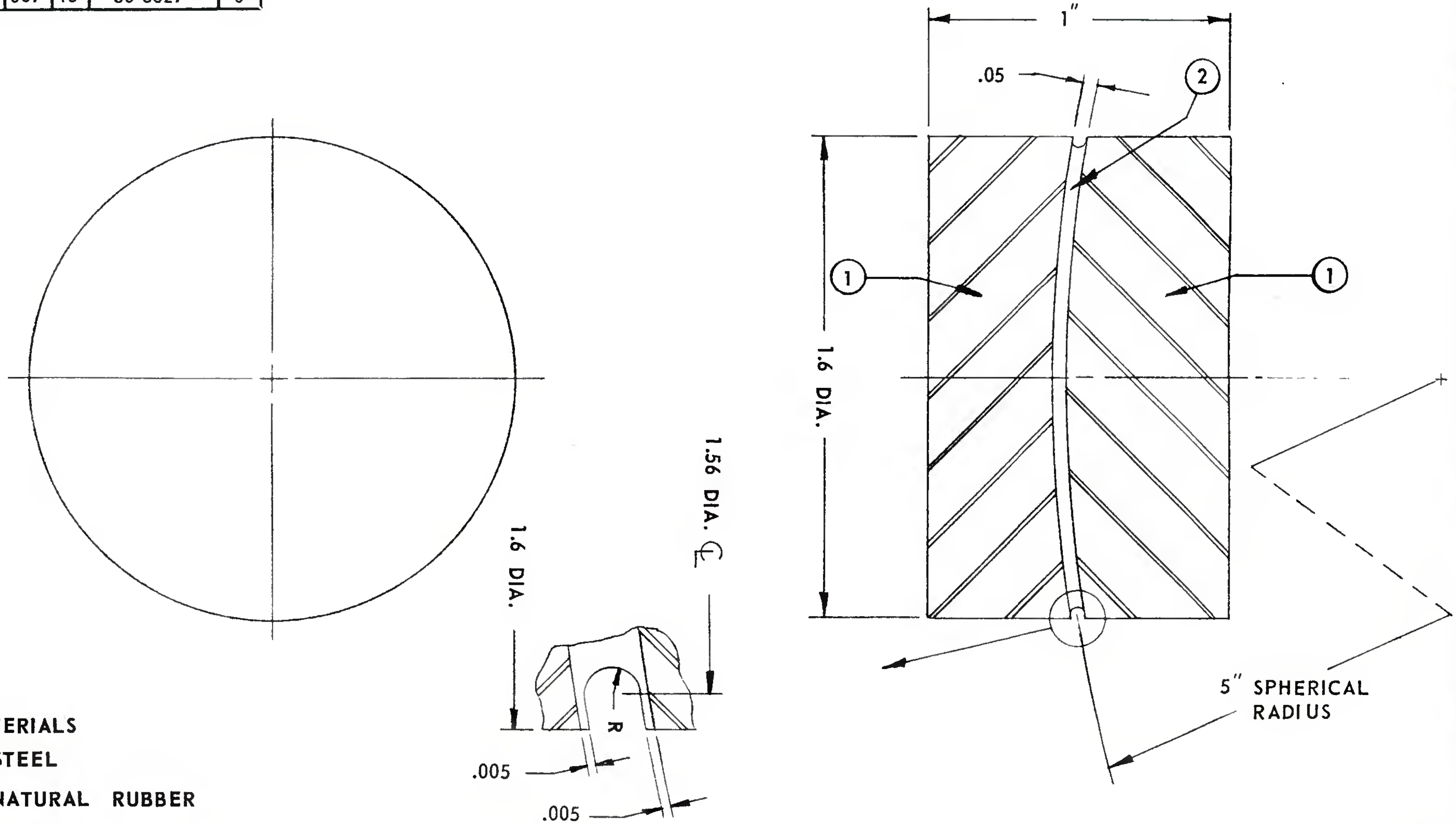
The conclusion of the coarse grid modelling study is as follows: The strain reducing effect of a radius undercut at the edge of the layer is missed and hence, elastomer strain results tend to be a little high (conservative). It is safest, especially when strain gradients are high, to incorporate a small element with a width about equal to its thickness at the edges of a layer. When this is done it is felt that a coarse grid model will consistantly give results that are slightly conservative.

CR DRAWING NO. B60 – 80 6627

REVISION

149	02	007	10	80 6627	0

DO NOT SCALE DRAWING
METRIC: 1 in. = 25.4 mm



MATERIALS
1 STEEL
2 NATURAL RUBBER

CUSTOMER A.M.M.R.C.

APPLICATION

CUSTOMER PART NO.

REVISIONS			
LTR	DATE	DESCRIPTION	BY

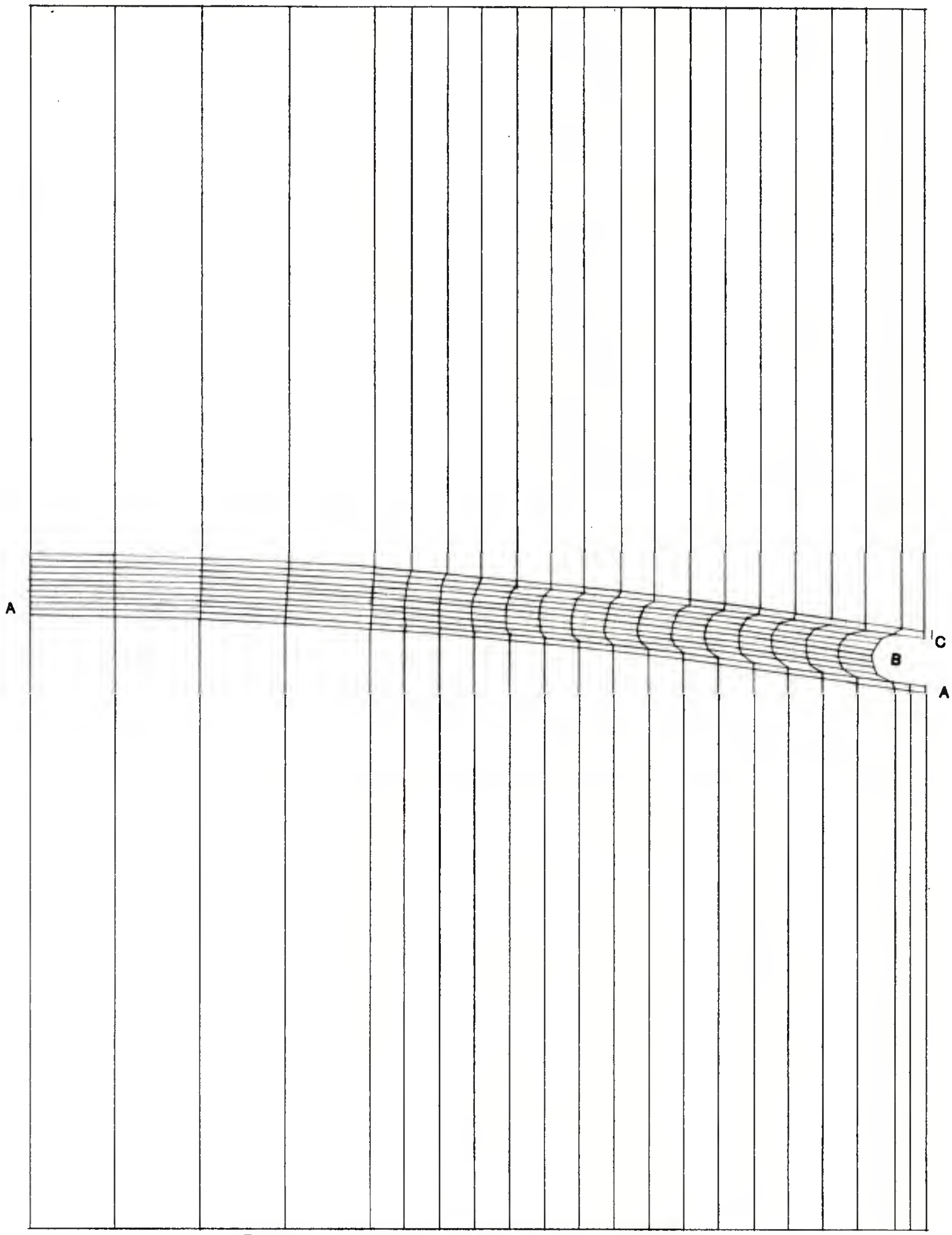
FIG. 1

C R INDUSTRIES
CHICAGO RAWHIDE MFG. CO.
Mechanical Products Division

NAME FATIGUE SPECIMEN

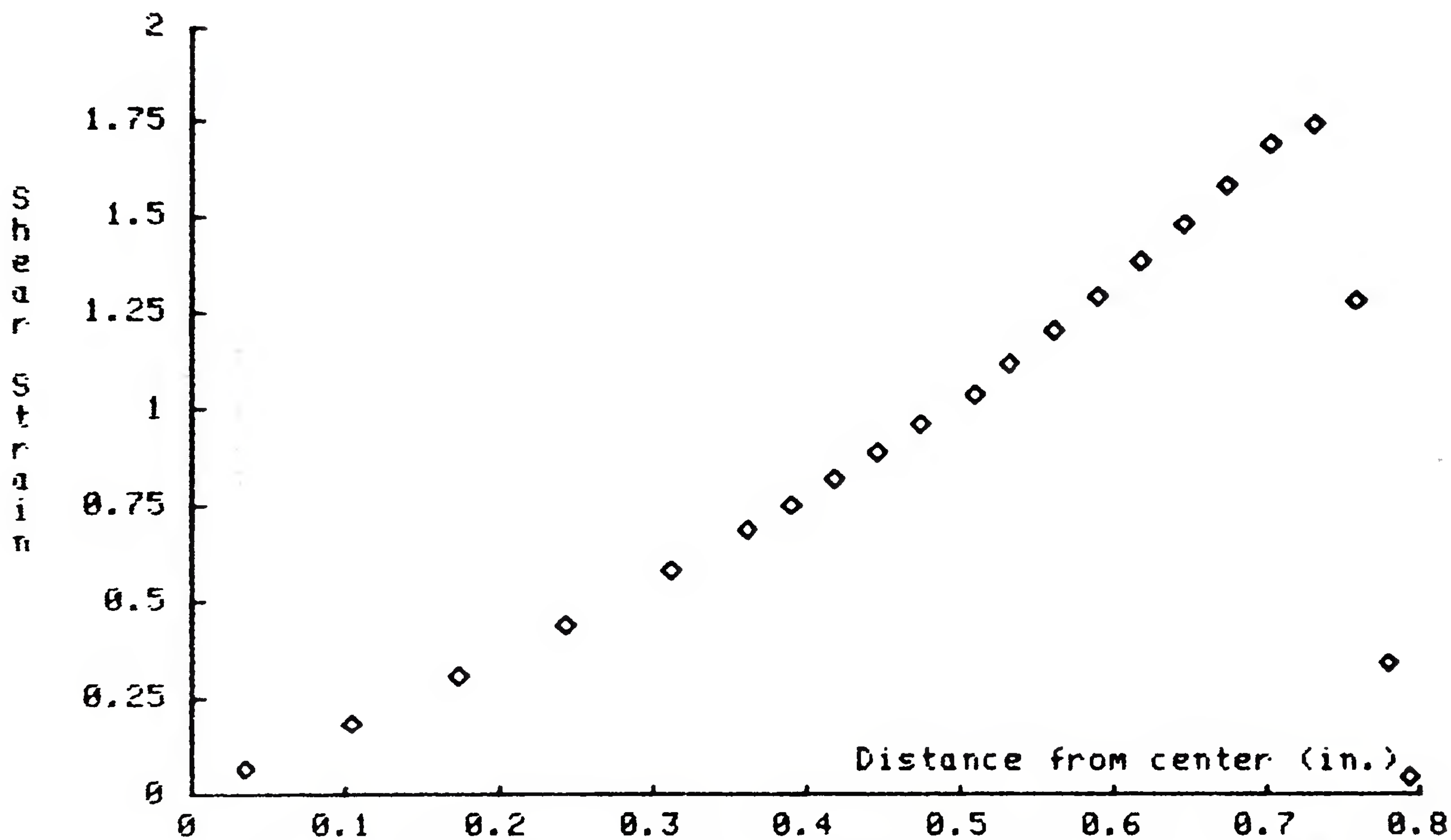
DATE 11-22-78 | SCALE 2X | DRAWN FM | CHECKED [illegible] | APPROVED AH

ORDER BY CR PART NO. B60 – 80 6627

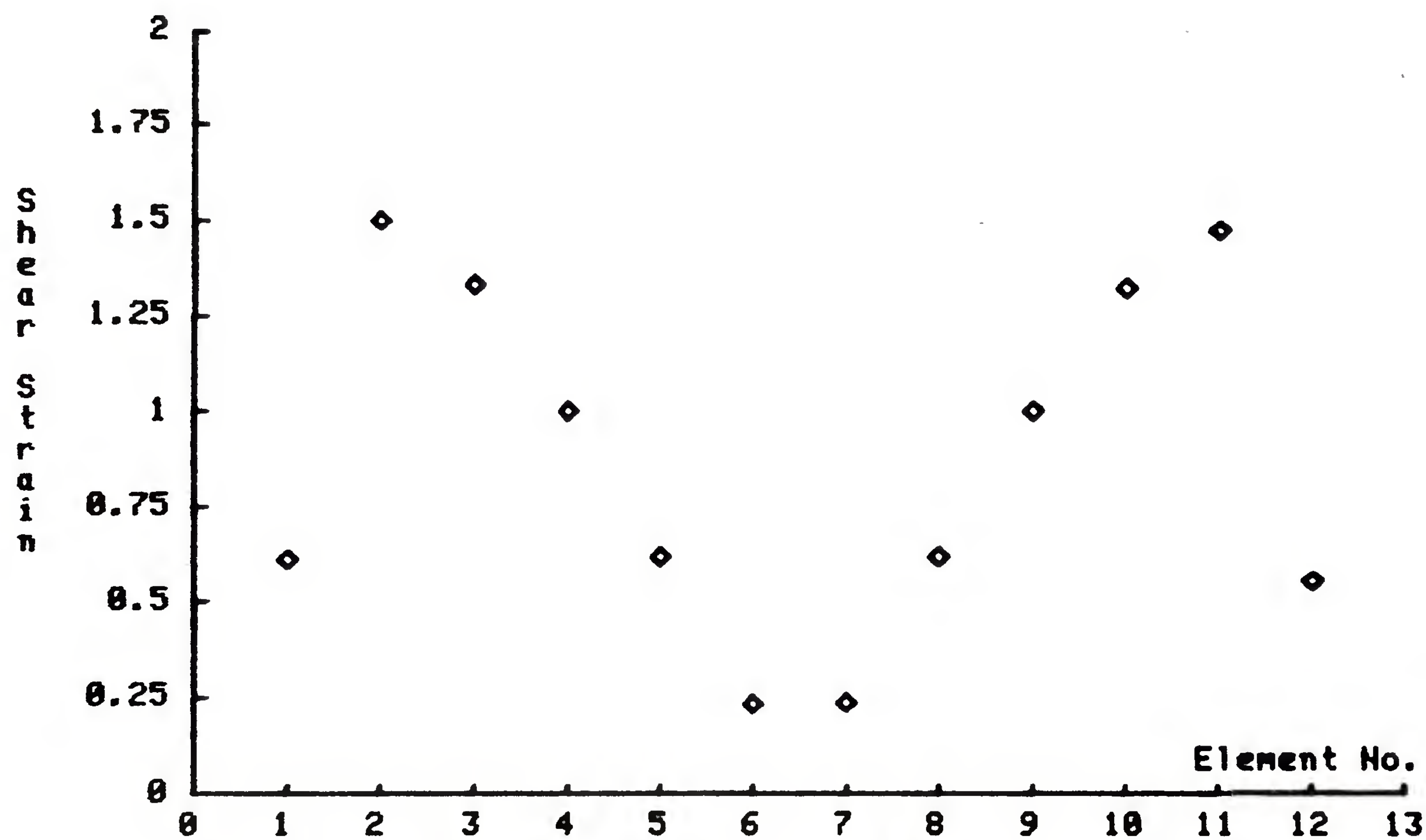


ELEMENT MODEL FOR FATIGUE TEST SPECIMEN

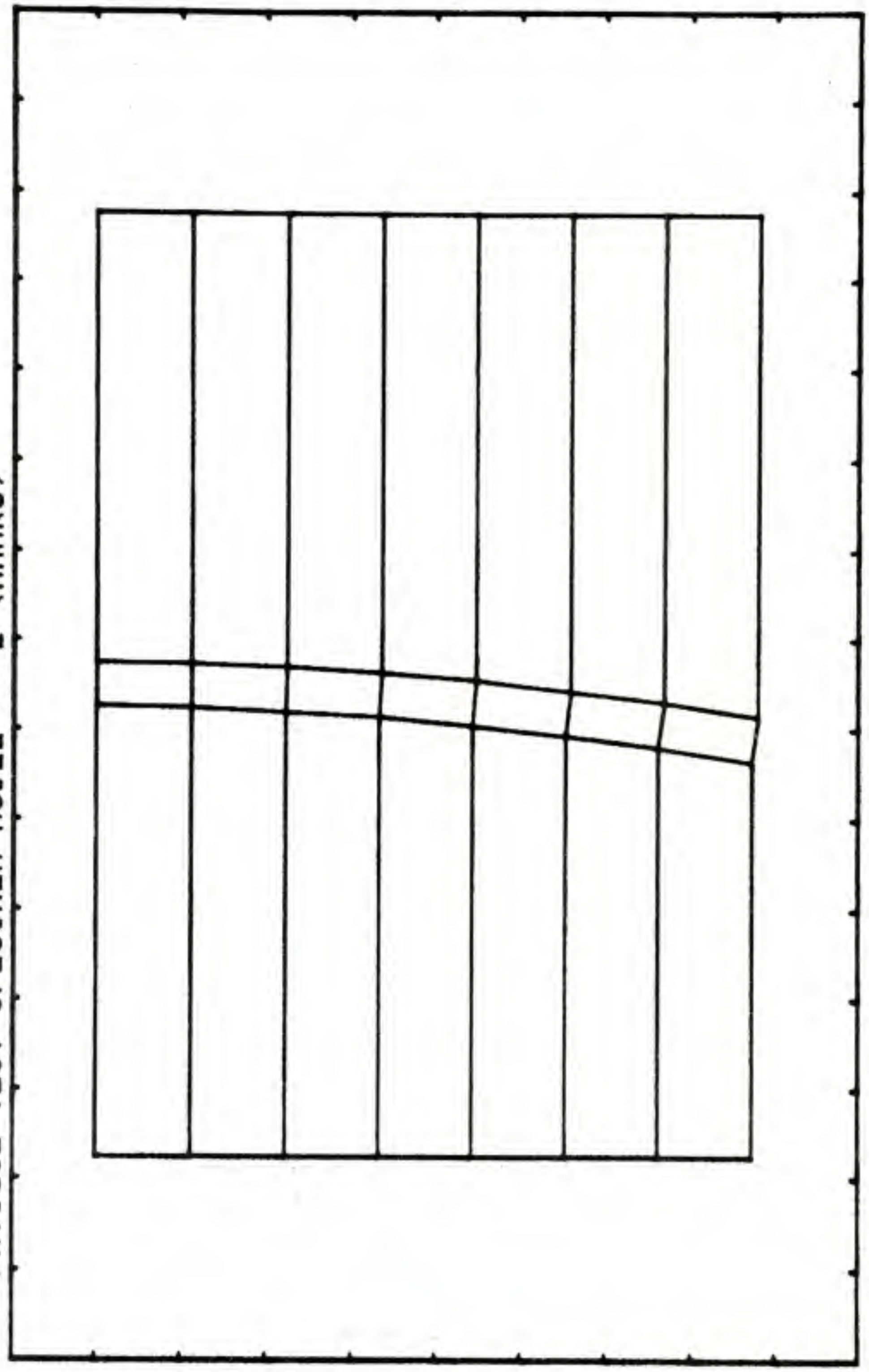
FIG. 2



STRAIN ALONG BOND LINE FOR AMMRC FATIGUE TEST SPECIMEN
MODEL -- 1 AT 5000 LBS. AXIAL LOAD (G = 200 PSI).
11/19/79
FIG. 3

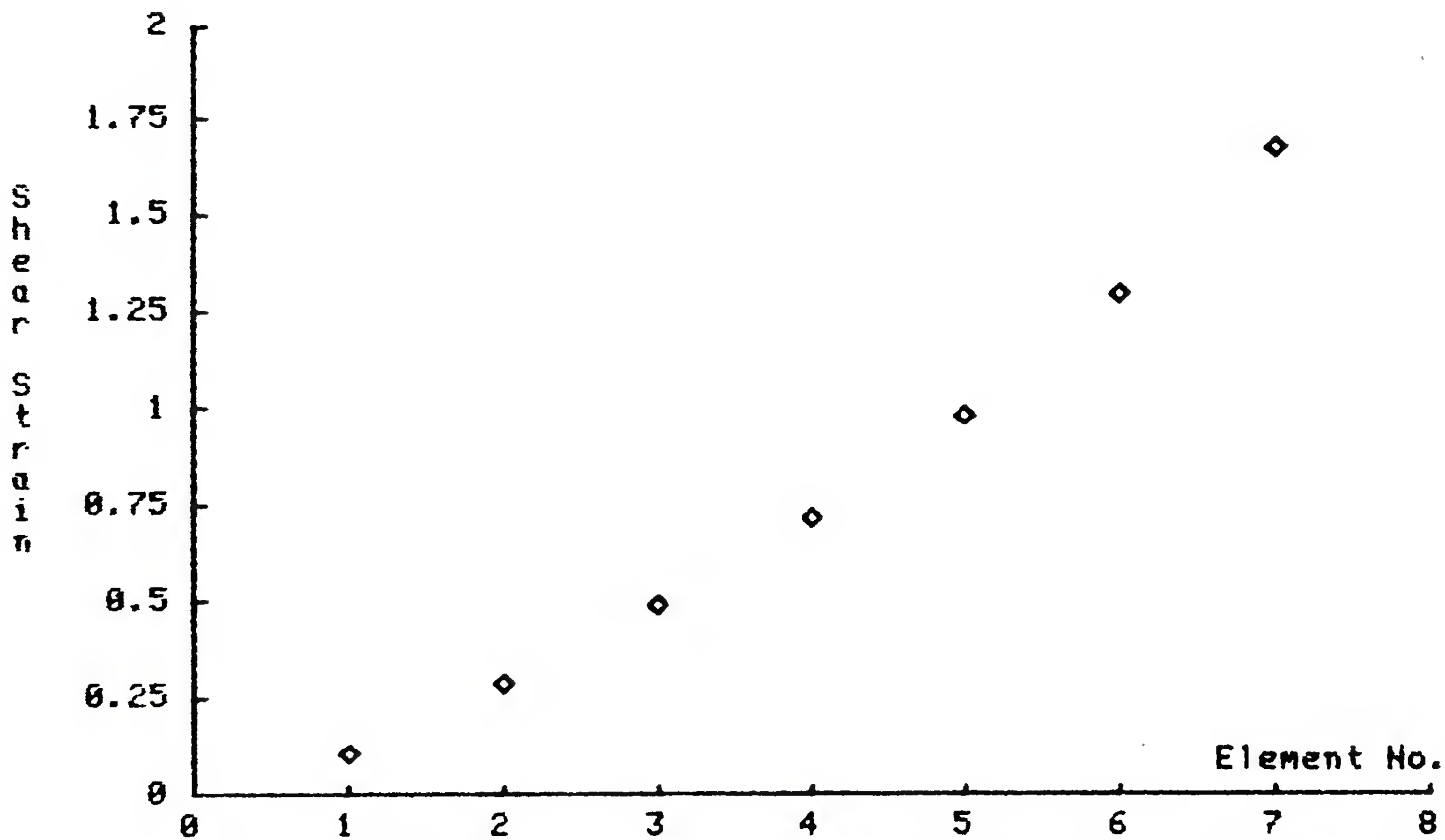


STRAIN ALONG RADIUS AT O.D. FOR AMMRC FATIGUE TEST SPECIMEN
MODEL -- 1 AT 5000 LBS. AXIAL LOAD (G = 200 PSI).
11/20/79
FIG. 4



FATIGUE TEST SPECIMEN MODEL -- 2 (AMMRC)

FIG. 5



STRAIN ALONG BOND LINE FOR AMMRC FATIGUE TEST SPECIMEN
MODEL -- 2 AT 5000 LBS. AXIAL LOAD (G = 200 PSI).
11/19/79
FIG. 6

FATIGUE TEST SPECIMEN MODEL 3 (AMMRC)

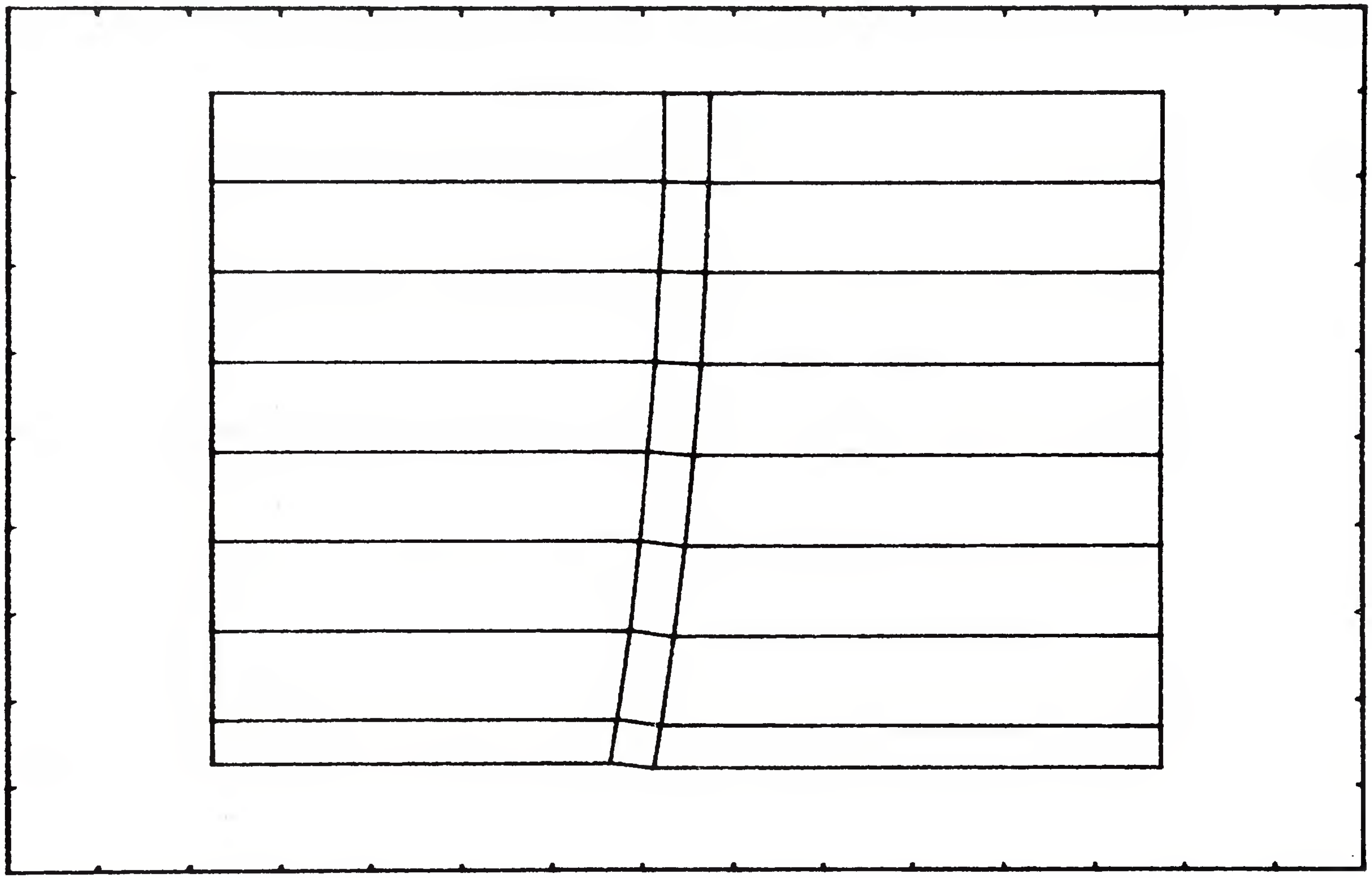
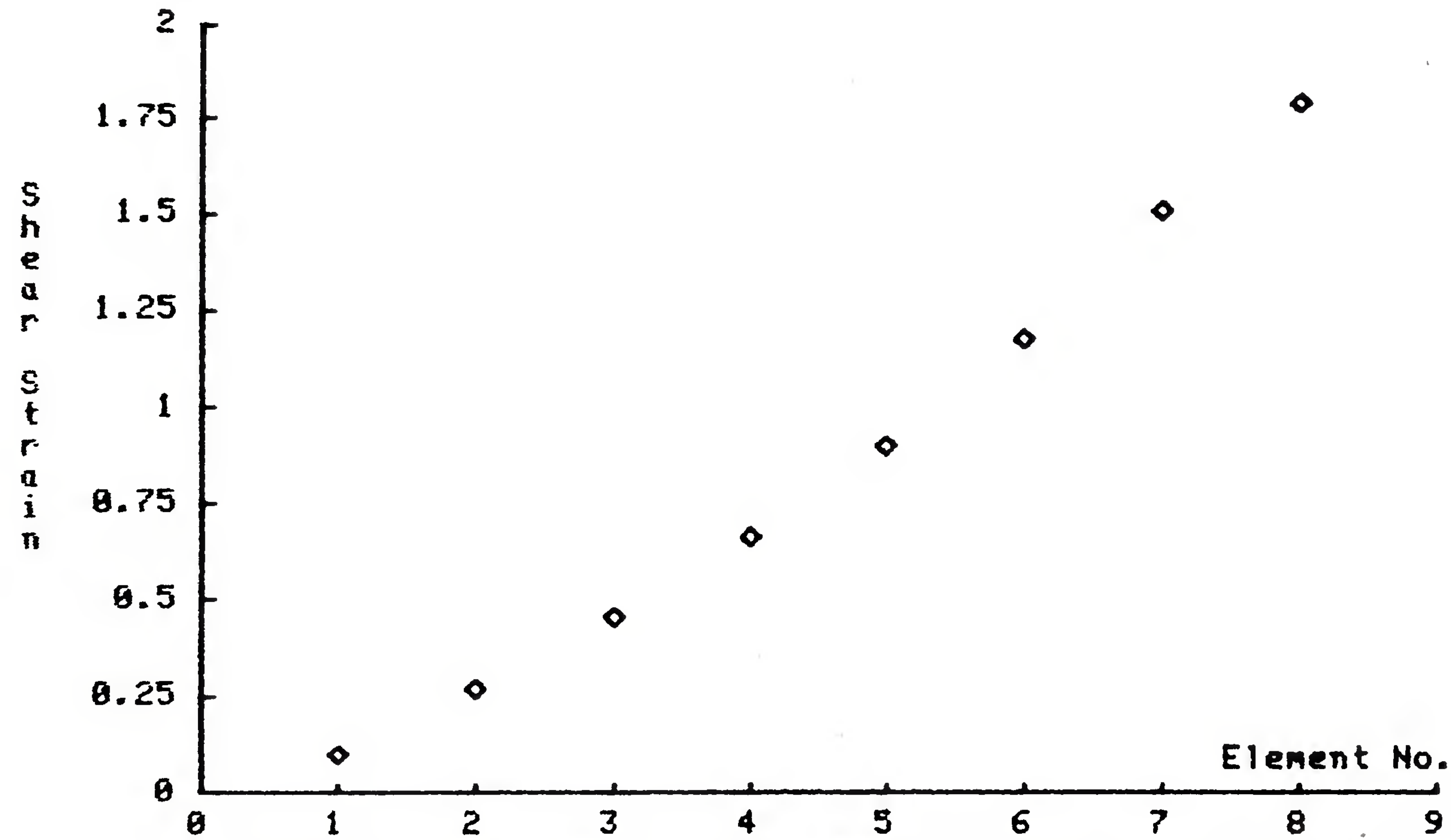


FIG. 7



STRAIN ALONG BOND LINE FOR AMMRC FATIGUE TEST SPECIMEN MODEL -- 3 AT 5000 LBS. AXIAL LOAD (G = 200 PSI).

11/19/79

FIG. 8

A P P E N D I X   I

```
1:$ FATIGUE TEST SPECIMEN AMMRC MODEL 1
2:SETUP,4,PRESCRIB,25
3:RUBBER,1,600,.4995
4:SSTEEL,2,30E6,.3
5:END,MATERIAL
6:1,1,2,1
7:0,.06946,.06946,0
8:4.47466,4.47466,4.47466,4.47466
9:3,1,4,1
10:.13891,.20833,.20833,.13891
11:4.47466,4.47466,4.47466,4.47466
12:5,1,6,1
13:.27771,.34704,.34704,.27771
14:4.47466,4.47466,4.47466,4.47466
15:7,1,8,1
16:.37555,.40405,.40405,.37555
17:4.47466,4.47466,4.47466,4.47466
18:9,1,10,1
19:.43254,.46101,.46101,.43254
20:4.47466,4.47466,4.47466,4.47466
21:11,1,12,1
22:.48947,.51791,.51791,.48947
23:4.47466,4.47466,4.47466,4.47466
24:13,1,14,1
25:.54633,.57474,.57474,.54633
26:4.47466,4.47466,4.47466,4.47466
27:15,1,16,1
28:.60312,.63149,.63149,.60312
29:4.47466,4.47466,4.47466,4.47466
30:17,1,18,1
31:.65984,.68816,.68816,.65984
32:4.47466,4.47466,4.47466,4.47466
33:19,1,20,1
34:.71646,.74474,.74474,.71646
```

```
35:4.47466,4.47466,4.47466,4.47466
36:20,1,21,1
37:.74474,.77299,.77299,.74474
38:4.47466,4.47466,4.47466,4.47466
39:1,2,6,3,1,1,1,1,POLAR,0,0
40:4.975,4.975,4.980,4.980
41:90,86,86,90
42:6,2,21,3,1,1,1,1,POLAR,0,0
43:4.975,4.975,4.980,4.980
44:86,81.06143,81.06143,86
45:1,4,6,5,1,1,1,1,POLAR,0,0
46:4.985,4.985,4.990,4.990
47:90,86,86,95
48:6,4,21,5,1,1,1,1,POLAR,0,0
49:4.985,4.985,4.990,4.990
50:86,81.21308,81.25994,86
51:1,6,6,7,1,1,1,1,POLAR,0,0
52:4.995,4.995,5,5
53:90,86,86,90
54:6,6,21,7,1,1,1,1,POLAR,0,0
55:4.995,4.995,5,5
56:86,81.28326,81.29043,86
57:1,8,6,9,1,1,1,1,POLAR,0,0
58:5.005,5.005,5.010,5.010
59:90,86,86,90
60:6,8,21,9,1,1,1,1,POLAR,0,0
61:5.005,5.005,5.010,5.010
62:86,81.28310,81.25958,86
63:1,10,6,11,1,1,1,1,POLAR,0,0
64:5.015,5.015,5.020,5.020
65:90,86,86,90
66:6,10,21,11,1,1,1,1,POLAR,0,0
67:5.015,5.015,5.020,5.020
68:86,81.21265,81.06125,86
```

```
69:1,11,6,12,1,1,1,1,POLAR,0,0
70:5.020,5.020,5.025,5.025
71:90,86,86,90
72:6,11,21,12,1,1,1,1,POLAR,0,0
73:5.020,5.020,5.025,5.025
74:86,81.06125,81.06125,86
75:1,13,2,13
76:0,.07016,.07016,0
77:5.5253,5.5253,5.5253,5.5253
78:3,13,4,13
79:.14031,.21043,.21043,.14031
80:5.5253,5.5253,5.5253,5.5253
81:5,13,6,13
82:.28050,.35053,.35053,.28050
83:5.5253,5.5253,5.5253,5.5253
84:7,13,8,13
85:.37933,.40811,.40811,.37933
86:5.5253,5.5253,5.5253,5.5253
87:9,13,10,13
88:.43689,.46565,.46565,.43689
89:5.5253,5.5253,5.5253,5.5253
90:11,13,12,13
91:.49439,.52312,.52312,.49439
92:5.5253,5.5253,5.5253,5.5253
93:13,13,14,13
94:.55183,.58052,.58052,.55183
95:5.5253,5.5253,5.5253,5.5253
96:15,13,16,13
97:.60919,.63785,.63785,.60919
98:5.5253,5.5253,5.5253,5.5253
99:17,13,18,13
100:.66648,.69509,.69509,.66648
101:5.5253,5.5253,5.5253,5.5253
102:19,13,20,13
```

```
103:.72368,.75224,.75224,.72368
104:5.5253,5.5253,5.5253,5.5253
105:20,13,21,13
106:.75224,.78078,.78078,.75224
107:5.5253,5.5253,5.5253,5.5253
108:21,11,22,12
109:.78,.8,.8,.78077
110:4.95903,4.95584,4.9609,4.96397
111:21,12,22,13
112:.78077,.8,.8,.78077
113:4.96397,4.9609,5.5253,5.5253
114:21,1,23,2
115:.77299,.8,.8,.77299
116:4.47466,4.47466,4.91026,4.91458
117:21,2,23,3
118:.77299,.8,.8,.77301
119:4.91458,4.91025,4.91532,4.91952
120:END,GRID
121:ILOOP,20,1
122:QUAD,2,1,1
123:IEND
124:JLOOP,10,1
125:ILOOP,20,1
126:QUAD,1,1,2
127:IEND
128:JEND
129:ILOOP,20,1
130:QUAD,2,1,12
131:IEND
132:QUAD,1,21,11
133:QUAD,2,21,12
134:QUAD,2,21,1
135:QUAD,2,22,1
136:QUAD,1,21,2
```

```
QUAD,1,22,2
ILOOP,22,1
BC,UZ,1,1,1,0
IEND
ILOOP,21,1
BC,PRESSURE,1,12,3,2486.79
IEND
END,ELEMENTS
PLOT,ELEMENTS,-.25,4.25,1,5.75,10
AXISYM
STOP
```

A P P E N D I X   II

```
$ FATIGUE TEST SPECIMEN MODEL -- 2 (AMMRC)
SETUP,4,PRESCRIB,10
RUBBER,1,600,.4995
SSTEEL,2,30E6,.3
END,MATERIAL
1,1,2,1
0,.11089,.11089,0
4.47446,4.47446,4.47446,4.47446
3,1,4,1
.22172,.33244,.33244,.22172
4.47446,4.47446,4.47446,4.47446
5,1,6,1
.44299,.55333,.55333,.44299
4.47446,4.47446,4.47446,4.47446
7,1,8,1
.66339,.77312,.77312,.66339
4.47446,4.47446,4.47446,4.47446
1,2,8,3,1,1,1,1,POLAR,0,0
4.975,4.975,5.025,5.025
90,81.06,81.06,90
1,4,2,4
0,.112,.112,0
5.5253,5.5253,5.5253,5.5253
3,4,4,4
.22394,.33578,.33578,.22394
5.5253,5.5253,5.5253,5.5253
5,4,6,4
.44744,.55889,.55889,.44744
5.5253,5.5253,5.5253,5.5253
7,4,8,4
.67005,.78089,.78089,.67005
5.5253,5.5253,5.5253,5.5253
END,GRID
ILOOP,7,1
```

```
35:QUAD,2,1,1
36:IEND
37:ILOOP,7,1
38:QUAD,1,1,2
39:IEND
40:ILOOP,7,1
41:QUAD,2,1,3
42:IEND
43:ILOOP,7,1
44:BC,UZ,1,1,1,0
45:IEND
46:ILOOP,7,1
47:BC,PRESSURE,1,3,3,2616
48:IEND
49:END,ELEMENTS
50:PLOT,ELEMENTS,-.1,4.25,.9,5.75,10
51:AXISYM
52:STOP
```

APPENDIX III

```
1:$ FATIGUE TEST SPECIMEN MODEL -- 3 (AMMRC)
2:SETUP,4,PRESCRIB,10
3:RUBBER,1,600,.4995
4:SSTEEL,2,30E6,.3
5:END,MATERIAL
6:1,1,2,1
7:0,.10375,.10375,0
8:4.47446,4.47446,4.47446,4.47446
9:3,1,4,1
10:.20746,.31108,.31108,.20746
11:4.47446,4.47446,4.47446,4.47446
12:5,1,6,1
13:.41475,.51787,.51787,.41475
14:4.47446,4.47446,4.47446,4.47446
15:7,1,8,1
16:.62095,.72376,.72376,.62095
17:4.47446,4.47446,4.47446,4.47446
18:8,1,9,1
19:.72376,.77312,.77312,.72376
20:4.47446,4.47446,4.47446,4.47446
21:1,2,8,3,1,1,1,1,POLAR,0,0
22:4.975,4.975,5.025,5.025
23:90,81.635,81.635,90
24:8,2,9,3,1,1,1,1,POLAR,0,0
25:4.975,4.975,5.025,5.025
26:81.635,81.06,81.06,81.635
27:1,4,2,4
28:0,.10486,.10486,0
29:5.5253,5.5253,5.5253,5.5253
30:3,4,4,4
31:.20967,.31140,.31140,.20967
32:5.5253,5.5253,5.5253,5.5253
33:5,4,6,4
34:.41898,.52339,.52339,.41898
```

```
35:5.5253,5.5253,5.5253,5.5253
36:7,4,8,4
37:.62756,.73146,.73146,.62756
38:5.5253,5.5253,5.5253,5.5253
39:8,4,9,4
40:.73146,.78089,.78089,.73146
41:5.5253,5.5253,5.5253,5.5253
42:END,GRID
43:ILOOP,8,1
44:QUAD,2,1,1
45:IEND
46:ILOOP,8,1
47:QUAD,1,1,2
48:IEND
49:ILOOP,8,1
50:QUAD,2,1,3
51:IEND
52:ILOOP,8,1
53:BC,UZ,1,1,1,0
54:IEND
55:ILOOP,8,1
56:BC,PRESSURE,1,3,3,2616
57:IEND
58:END,ELEMENTS
59:PLOT,ELEMENTS,-.1,4.25,.9,5.75,10
60:AXISYM
61:STOP
```

SECTION 5.

EXPERIMENTAL DATA ON THE AMMRC ENDURANCE SPECIMEN

The report in Appendix I. of this section gives experimental results of endurance tests on thirteen AMMRC fatigue specimens (see Table 1 of the Appendix). The data is plotted in Fig. 1. The report gives the following fifth power curve fitted to the life (N) vs. load (L) data;

$$N = \left(\frac{29,500}{L}\right)^5$$

In the previous section we found a maximum shear strain of 1.8 for a load of 5000 lbs. on the coarse grid model, so that the shear strain is given by

$$\gamma = \frac{L}{2778}$$

Substituting we find the life to be

$$N = \left(\frac{10.6}{\gamma}\right)^5$$

Since this experimental endurance curve was obtained from an actual elastomeric bearing based on the materials, analytic and measuring techniques normally used in elastomeric bearings it should be specific to these conditions. It does, however, compare well with a published general relationship listed in Section 3 as

$$N = \left(\frac{12.5}{\gamma}\right)^5$$

A documentation of the criterion of first damage used on the AMMRC endurance specimen is given in Appendix II. Fig. 1 is a photomicrograph of the elastomer edge from the fatigue specimen before test. Fig. 2 is a photomicrograph of the same edge after test. Fig. 3 is a line drawing interpretation of the significance of these photos. Admittedly this criterion of first damage was stringent, but, when scaled up to elastomeric bearings the size of the Blackhawk main rotor bearings, it is felt that this criterion is consistant with that used for the larger bearings.

A P P E N D I X I

Chicago Rawhide Mfg. Co., 2517 Pan Am Blvd., Elk Grove Village, Ill. 60007, 312/595-4620

CR INDUSTRIES

TEST REPORT

AMMRC Contract DAA-46-78-C-0029

September 27, 1979

by

Emmet M. Skroch

Test Lab Manager

Test Report

Testing of the AMMRC Fatigue Specimens (CR 80 6627) has been completed. A total of 13 specimens were tested, until evidence of first damage was observed.

Compressive axial loading of the test parts was done using a sine wave forcing function at a cycling rate of 4.2 Hz. The minimum compressive axial load for each test specimen was established as 10% of the peak-to-peak cyclic loading.

Table I shows the loading spectrum that was used in testing the fatigue plugs. Figure 1 is a plot of the half amplitude cyclic loading vs. the cycles to first damage. All observation for first damage were made using a microscope with 15 x magnification. The solid line shown in Figure 1 is a 5th power curve derived from the empirical data. The line as shown in Figure 1 is not continuous. For cyclic loads of approximately 1700 lbs. and less a knee is evident. This knee is an indication of infinite fatigue life. The continuous portion of this curve can be described by the following equation:

$$N = \left(\frac{29,500}{L}\right)^5$$

In the above equations

N is the number of cycles

L is the half amplitude cyclic load

	LOAD (lbs)	CYCLES
1.	5050 ± 4200	1.75×10^4
2.	4320 ± 3600	3.00×10^4
3.	3900 ± 3250	5.69×10^4
4.	3900 ± 3250	5.10×10^4
5.	3660 ± 3050	7.00×10^4
6.	3510 ± 2925	6.00×10^4
7.	3120 ± 2600	1.50×10^5
8.	2925 ± 2438	4.20×10^5
9.	2640 ± 2200	4.70×10^5
10.	2400 ± 2000	9.00×10^5
11.	2100 ± 1750	1.30×10^6
12.	2040 ± 1700	2.00×10^6
13.	1950 ± 1625	1.60×10^7

TABLE I

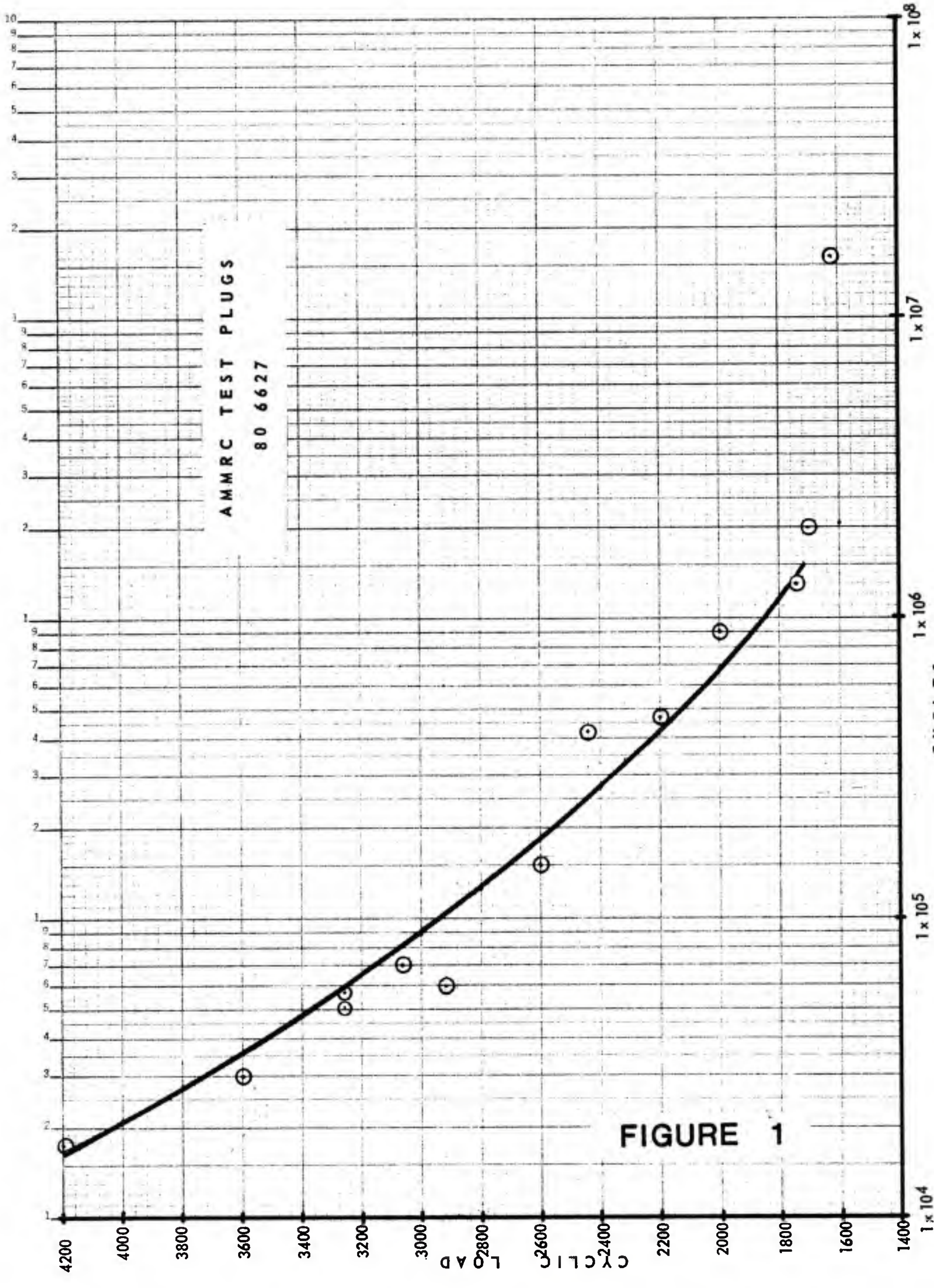
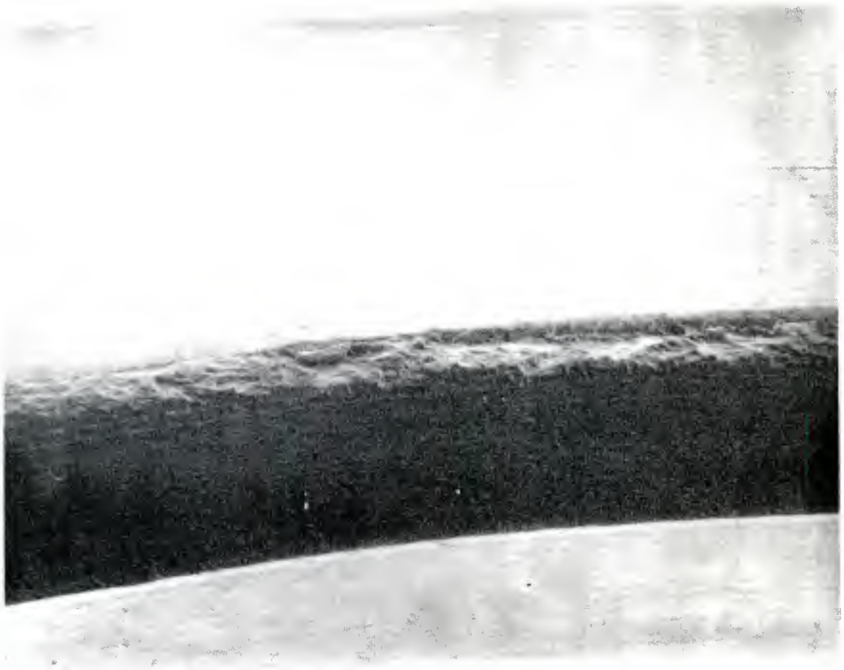

AMMRC TEST PLUGS
80 6627
CYCLES
CYCLIC LOAD
1 x 10^4
1 x 10^5
1 x 10^6
1 x 10^7
1 x 10^8
4200
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400

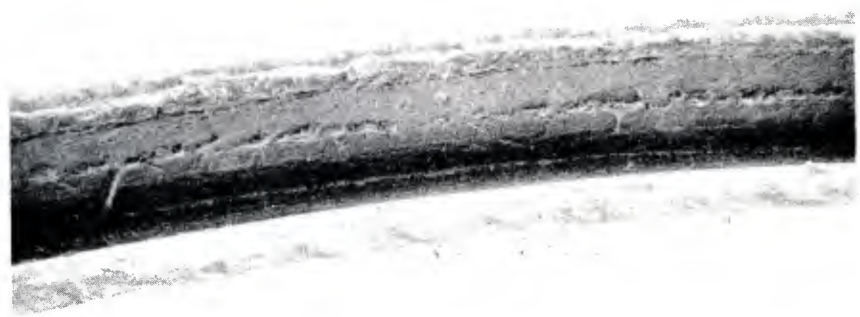
FIGURE 1

APPENDIX II



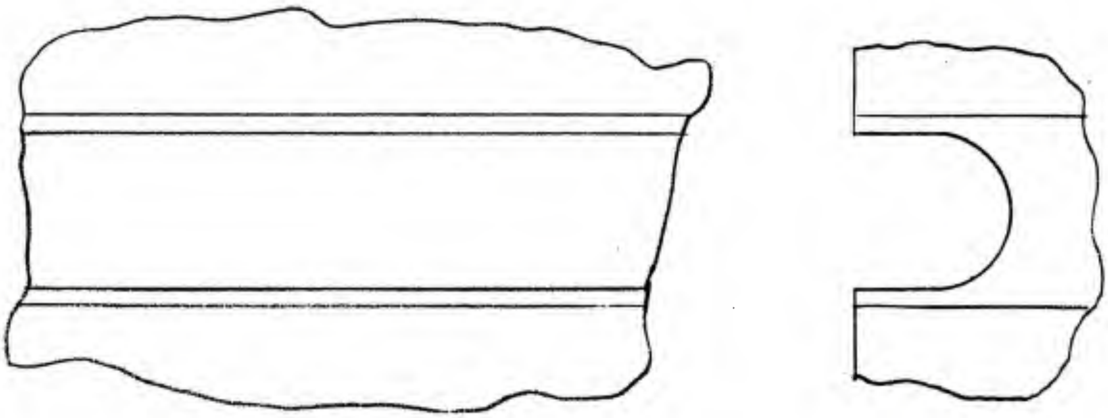
FATIGUE SPECIMEN BEFORE TEST

FIG. 1

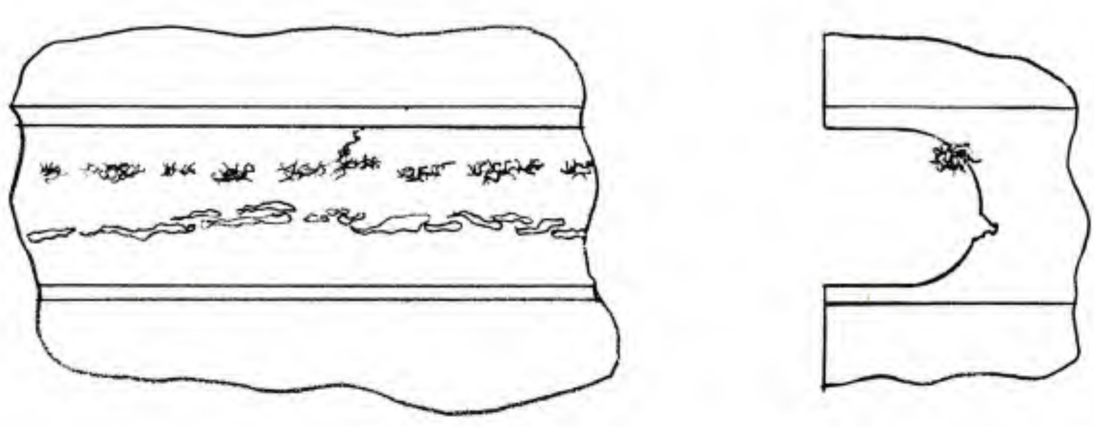


FATIGUE SPECIMEN AFTER TEST

FIG. 2



FATIGUE SPECIMEN ELASTOMER EDGE
BEFORE TEST



FATIGUE SPECIMEN ELASTOMER EDGE
AFTER TEST
FIG. 3

SECTION 6.

ANALYSIS OF THE BLACKHAWK MAIN ROTOR THRUST BEARING

The subject covered in this section is an analysis of the elastomer strain and metal shell stress in the Blackhawk main rotor elastomeric thrust bearing (see Figure 1.) A prediction of the life of the thrust bearing will be given based on this data. As reference it is suggested that the Sections 2 and 3, covering finite element analysis and the use of strain data to predict the life of elastomeric parts, be reviewed. The analysis of this thrust bearing was straight forward and superposition was not required.

The first model for stress or strain at the I.D. of the thrust bearing is shown in Figure 2 and enlarged sections in Figures 3 and 4. Note, the small element at the I.D. allows "mid-side node" stress or strain values for a location close to the edge. The model for O.D. stress and strain is shown in Figure 5 and blow-ups in Figures 6 and 7. A listing of the programs are given in the Appendix.

The maximum stress in the A-70 C.P. titanium shells for a 68,000 pound C.F. load is shown in Figures 8 and 9 to be 70 ksi. With a 70 ksi yield point the stress in the shells after the first cycle may be considered to be 35 ± 35 ksi. The metal shells, therefore, are not expected to suffer endurance failure within the expected life of this bearing.

The elastomer strain for the 68,000 pound C.F. load is shown in Figures 10 and 11. The elastomer strain due to pitch change can be calculated directly from first principles. For a 1 degree rotation

$$\gamma = \frac{R\Theta}{t}$$

$$\gamma_{I.D.} = \frac{1.5\ (\pi/180)}{(10*0.025+45*0.030} = 0.0164$$

$$\gamma_{O.D.} = \frac{2.55\ (\pi/180)}{(10*0.025+45*0.030)} = 0.0278$$

Where: γ is the shear strain

Θ is the angle of rotation (in radians)

t is the total elastomer thickness

R is the radius

Note; the above may seem like an oversimplification, but is identical to the result obtained by an integral solution. The finite element backup solution is shown in Figure 12.

The spherical and the thrust bearing share the total blade pitch change.

Spring rate of the spherical bearing = 1000 in.-lb./degree

Spring rate of 80 9589 = 120 in.-lb./degree

$$\left(\frac{1000}{1000 + 120}\right) 100 = 89.3\% \text{ of the total pitch change for 80 9589.}$$

The effective pitch change angle found from S.E.S. 701054

Rev. 4 by the method previously described (see Appendix of Section 3) is 6.54 degrees.

The following is a sample calcultaion of the life limiting combination of pitch change and centrifugal force strain calculated for the I.D. of the first layer (see the Appendix of Section 3);

γ =

$$\sqrt[5]{\frac{258*60(6.54*0.893*0.0164)^5 + \left(\frac{7.29}{2} * \frac{82000}{68000}\right)^5 + 2*\left(\frac{7.29}{2}\right)^5}{258*60 + 1.0 + 2.0}}$$

γ = .717

The life limiting strain at the I.D. is shown for all the layers in Figure 13. The results for a similar procedure for the O.D. is shown in Figure 14.

On the basis of this analysis, first damage is predicted at

$$\text{Life} = \left(\frac{10.6}{.717}\right)^5 * \frac{1}{60*258}$$

$$= 46 \text{ hrs}$$

The predicted location for this first damage is at the I.D. of the first layer next to the flanged end fitting (see Figures 13 and 14).

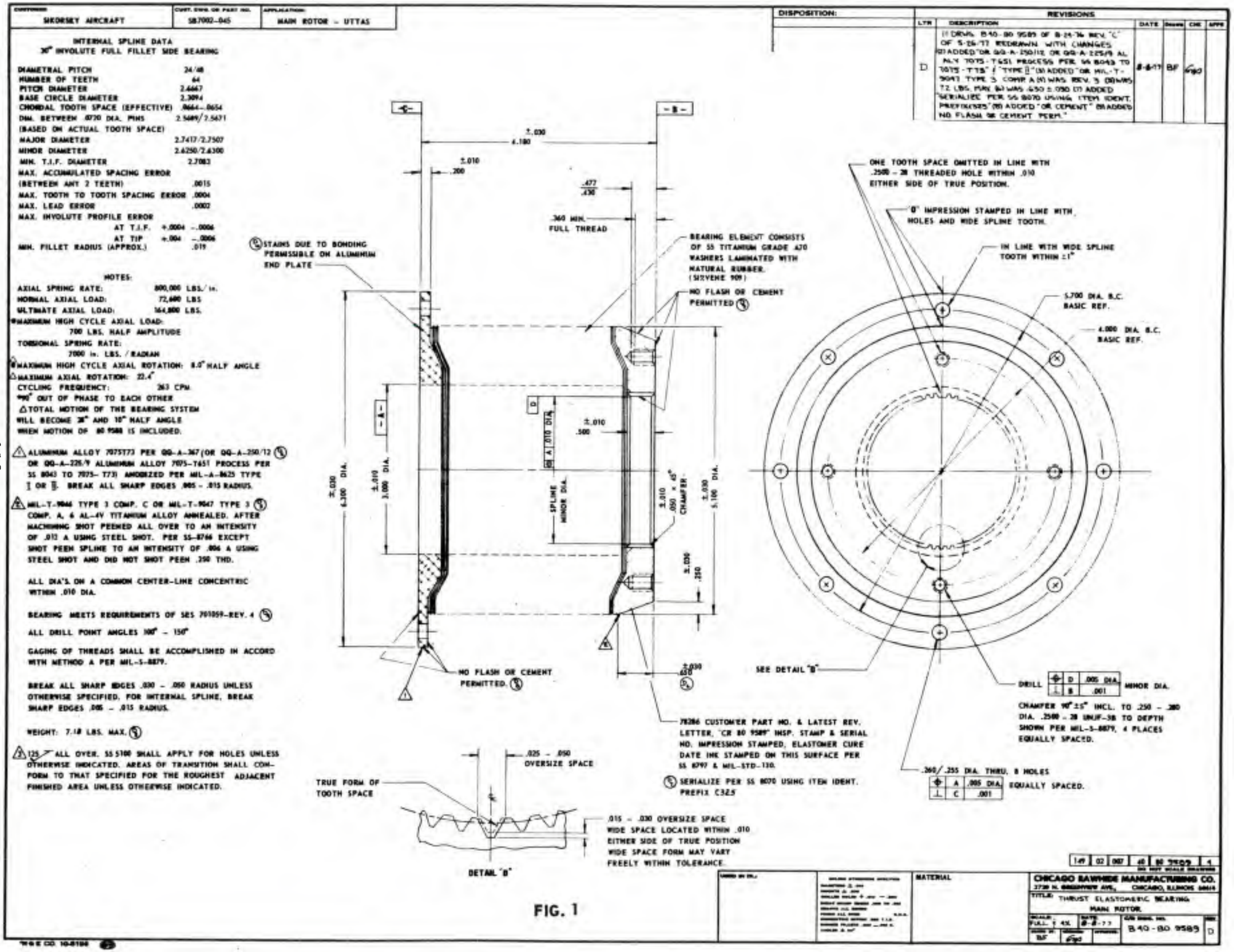

CUSTOMER: SIKORSKY AIRCRAFT
CUST. DWG. OR PART NO.: SB7002-045
APPLICATION: MAIN ROTOR - UTTAS
DISPOSITION:
REVISIONS
INTERNAL SPLINE DATA
30° INVOLUTE FULL FILLET SIDE BEARING
DIAMETRAL PITCH 24/48
NUMBER OF TEETH 64
PITCH DIAMETER 2.6667
BASE CIRCLE DIAMETER 2.3094
CHORDAL TOOTH SPACE (EFFECTIVE) .0664-.0654
DIM. BETWEEN .0720 DIA. PINS 2.5469/2.5471
(BASED ON ACTUAL TOOTH SPACE)
MAJOR DIAMETER 2.7417/2.7507
MINOR DIAMETER 2.6250/2.6300
MIN. T.I.F. DIAMETER 2.7083
MAX. ACCUMULATED SPACING ERROR (BETWEEN ANY 2 TEETH) .0015
MAX. TOOTH TO TOOTH SPACING ERROR .0004
MAX. LEAD ERROR .0002
MAX. INVOLUTE PROFILE ERROR AT T.I.F. +.0004 -.0006 AT TIP +.004 -.0006
MIN. FILLET RADIUS (APPROX.) .019
NOTES:
AXIAL SPRING RATE: 800,000 LBS./in.
NORMAL AXIAL LOAD: 72,600 LBS
ULTIMATE AXIAL LOAD: 164,800 LBS.
MAXIMUM HIGH CYCLE AXIAL LOAD: 700 LBS. HALF AMPLITUDE
TORSIONAL SPRING RATE: 7000 in. LBS. / RADIAN
MAXIMUM HIGH CYCLE AXIAL ROTATION: 8.0° HALF ANGLE
MAXIMUM AXIAL ROTATION: 22.4°
CYCLING FREQUENCY: 263 CPM
90° OUT OF PHASE TO EACH OTHER
TOTAL MOTION OF THE BEARING SYSTEM WILL BECOME 28° AND 10° HALF ANGLE WHEN MOTION OF 80 9588 IS INCLUDED.
ALUMINUM ALLOY 7075T73 PER QQ-A-367 (OR QQ-A-250/12 OR QQ-A-225/9 ALUMINUM ALLOY 7075-T651 PROCESS PER SS 8043 TO 7075-T73) ANODIZED PER MIL-A-8625 TYPE I OR II. BREAK ALL SHARP EDGES .005 - .015 RADIUS.
MIL-T-9046 TYPE 3 COMP. C OR MIL-T-9047 TYPE 3 COMP. A, 6 AL-4V TITANIUM ALLOY ANNEALED. AFTER MACHINING SHOT PEENED ALL OVER TO AN INTENSITY OF .012 A USING STEEL SHOT. PER SS-8766 EXCEPT SHOT PEEN SPLINE TO AN INTENSITY OF .006 A USING STEEL SHOT AND DID NOT SHOT PEEN .250 THD.
ALL DIA'S. ON A COMMON CENTER-LINE CONCENTRIC WITHIN .010 DIA.
BEARING MEETS REQUIREMENTS OF SES 701059-REV. 4
ALL DRILL POINT ANGLES 100° - 150°
GAGING OF THREADS SHALL BE ACCOMPLISHED IN ACCORD WITH METHOD A PER MIL-S-8879.
BREAK ALL SHARP EDGES .030 - .050 RADIUS UNLESS OTHERWISE SPECIFIED. FOR INTERNAL SPLINE, BREAK SHARP EDGES .005 - .015 RADIUS.
WEIGHT: 7.18 LBS. MAX.
125 ALL OVER. SS 5100 SHALL APPLY FOR HOLES UNLESS OTHERWISE INDICATED. AREAS OF TRANSITION SHALL CONFORM TO THAT SPECIFIED FOR THE ROUGHEST ADJACENT FINISHED AREA UNLESS OTHERWISE INDICATED.
STAINS DUE TO BONDING PERMISSIBLE ON ALUMINUM END PLATE
BEARING ELEMENT CONSISTS OF 55 TITANIUM GRADE A70 WASHERS LAMINATED WITH NATURAL RUBBER. (SIZVENE 909)
NO FLASH OR CEMENT PERMITTED
.360 MIN. FULL THREAD
SPLINE MINOR DIA.
CHAMFER
NO FLASH OR CEMENT PERMITTED.
78286 CUSTOMER PART NO. & LATEST REV. LETTER, "CR 80 9589" INSP. STAMP & SERIAL NO. IMPRESSION STAMPED, ELASTOMER CURE DATE INK STAMPED ON THIS SURFACE PER SS 8797 & MIL-STD-130.
SERIALIZE PER SS 8070 USING ITEM IDENT. PREFIX C325
ONE TOOTH SPACE OMITTED IN LINE WITH .2500 - 28 THREADED HOLE WITHIN .010 EITHER SIDE OF TRUE POSITION.
"0" IMPRESSION STAMPED IN LINE WITH HOLES AND WIDE SPLINE TOOTH.
IN LINE WITH WIDE SPLINE TOOTH WITHIN ±1°
5.700 DIA. B.C. BASIC REF.
4.800 DIA. B.C. BASIC REF.
SEE DETAIL "B"
DRILL MINOR DIA.
CHAMFER 90°±5° INCL. TO .250 - .280 DIA. .2500 - 28 UNJF-3B TO DEPTH SHOWN PER MIL-S-8879, 4 PLACES EQUALLY SPACED.
.260/.255 DIA. THRU. 8 HOLES EQUALLY SPACED.
TRUE FORM OF TOOTH SPACE
.025 - .050 OVERSIZE SPACE
.015 - .030 OVERSIZE SPACE WIDE SPACE LOCATED WITHIN .010 EITHER SIDE OF TRUE POSITION WIDE SPACE FORM MAY VARY FREELY WITHIN TOLERANCE.
DETAIL "B"
MATERIAL
CHICAGO RAWHIDE MANUFACTURING CO.
TITLE: THRUST ELASTOMERIC BEARING MAIN ROTOR
B40-80 9589 D

FIG. 1

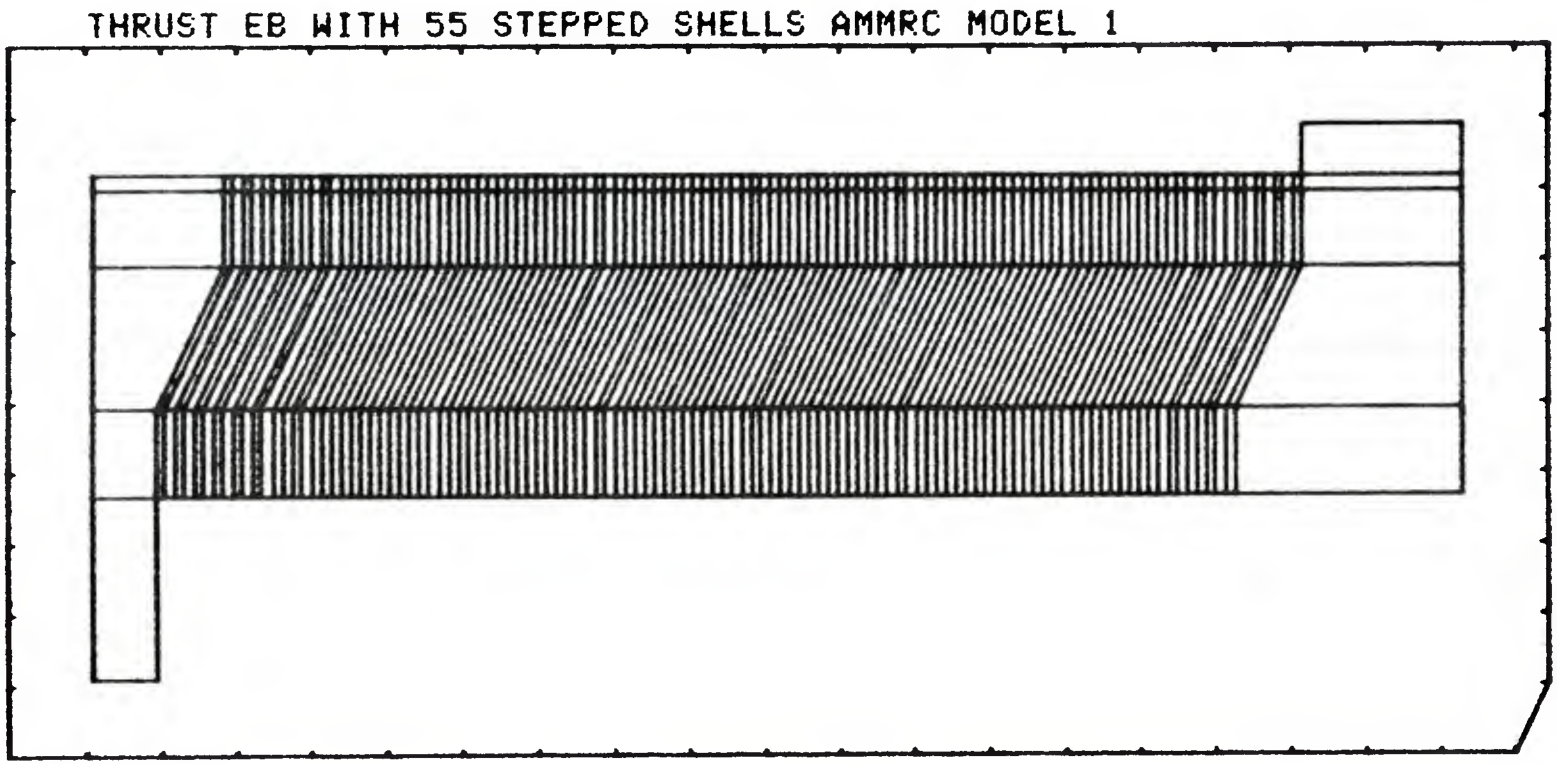
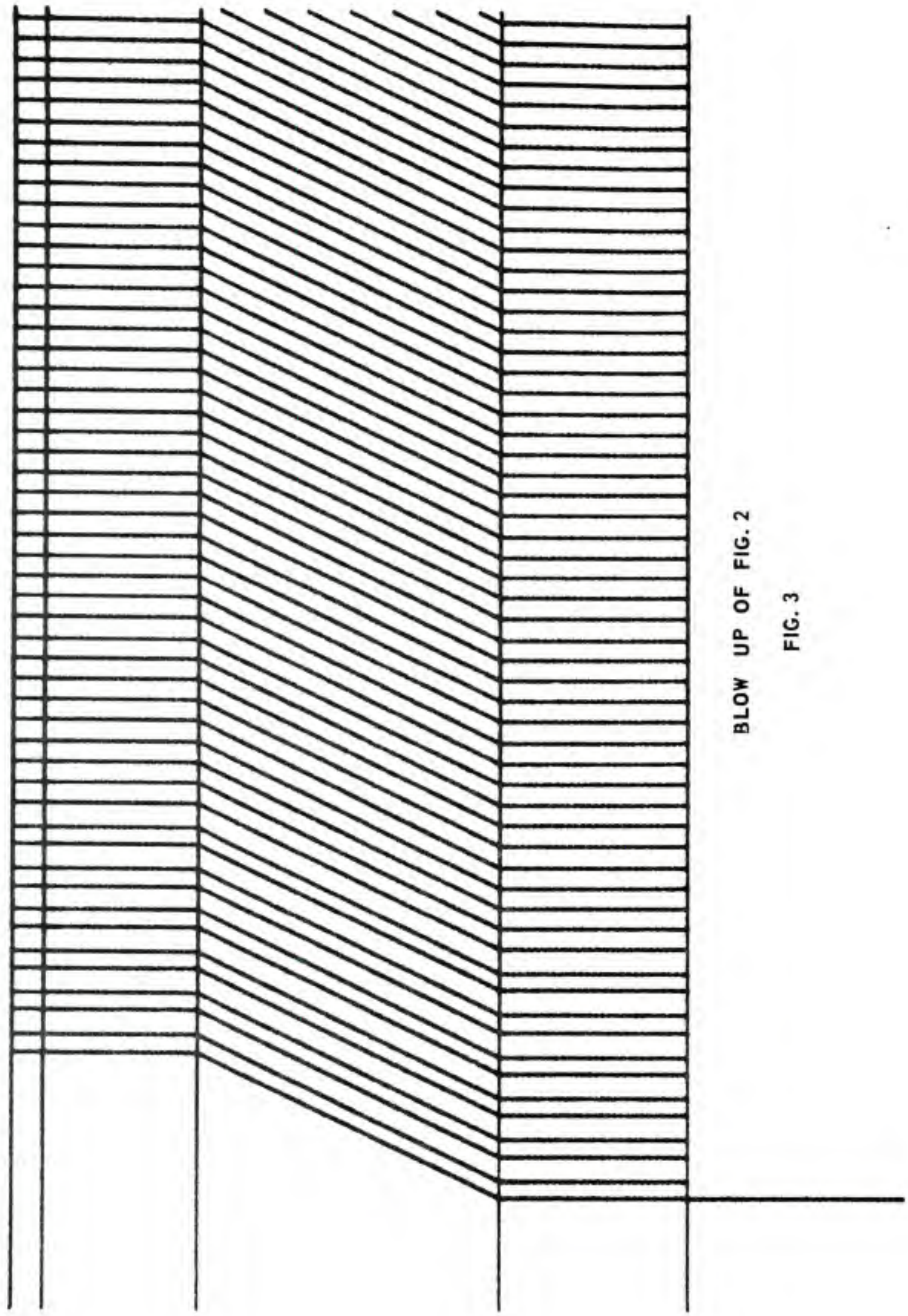
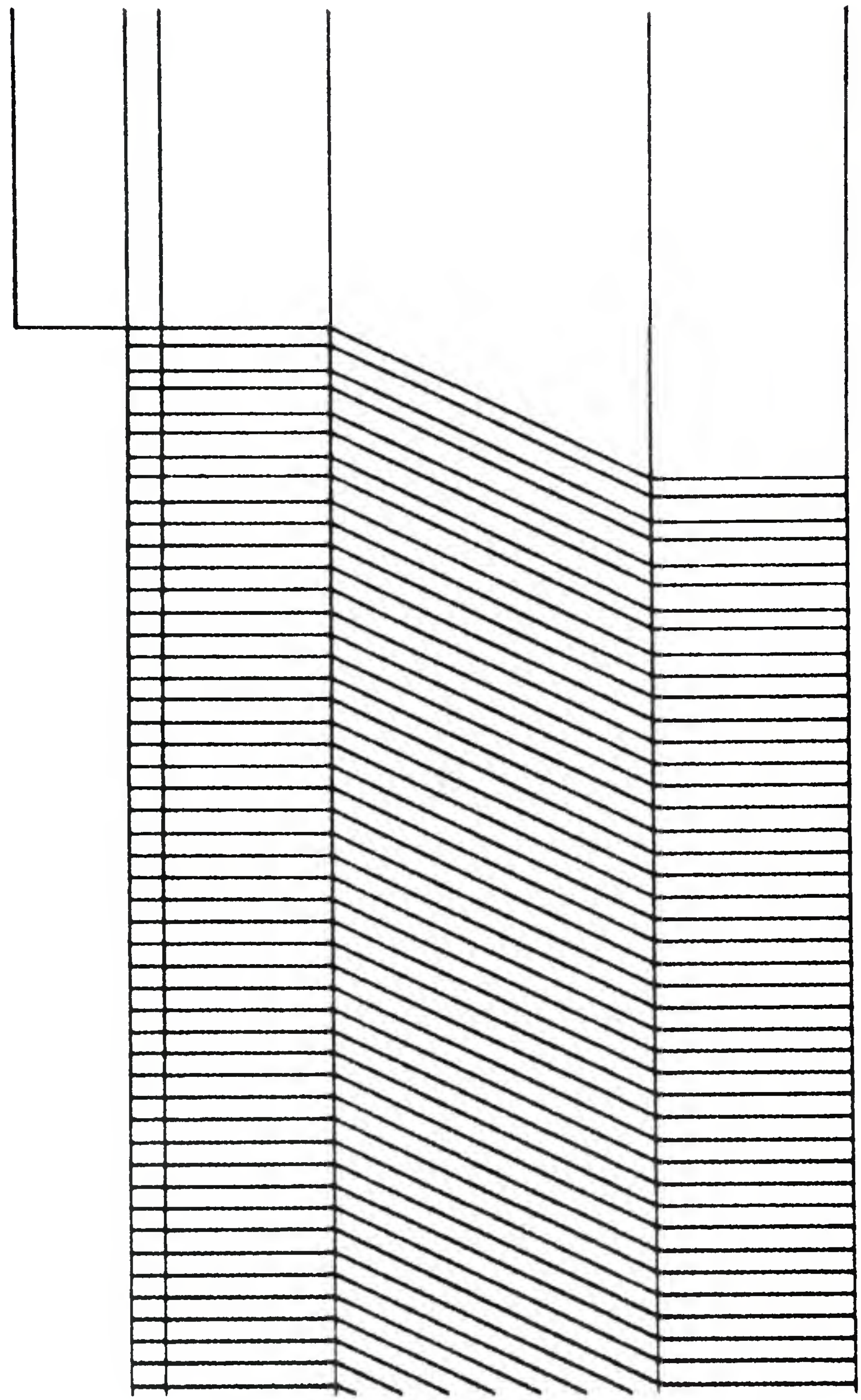


FIG. 2



BLOW UP OF FIG. 2

FIG. 3



BLOW UP OF FIG. 2

FIG. 4

THRUST EB WITH 55 STEPPED SHELLS AMMRC MODEL 2

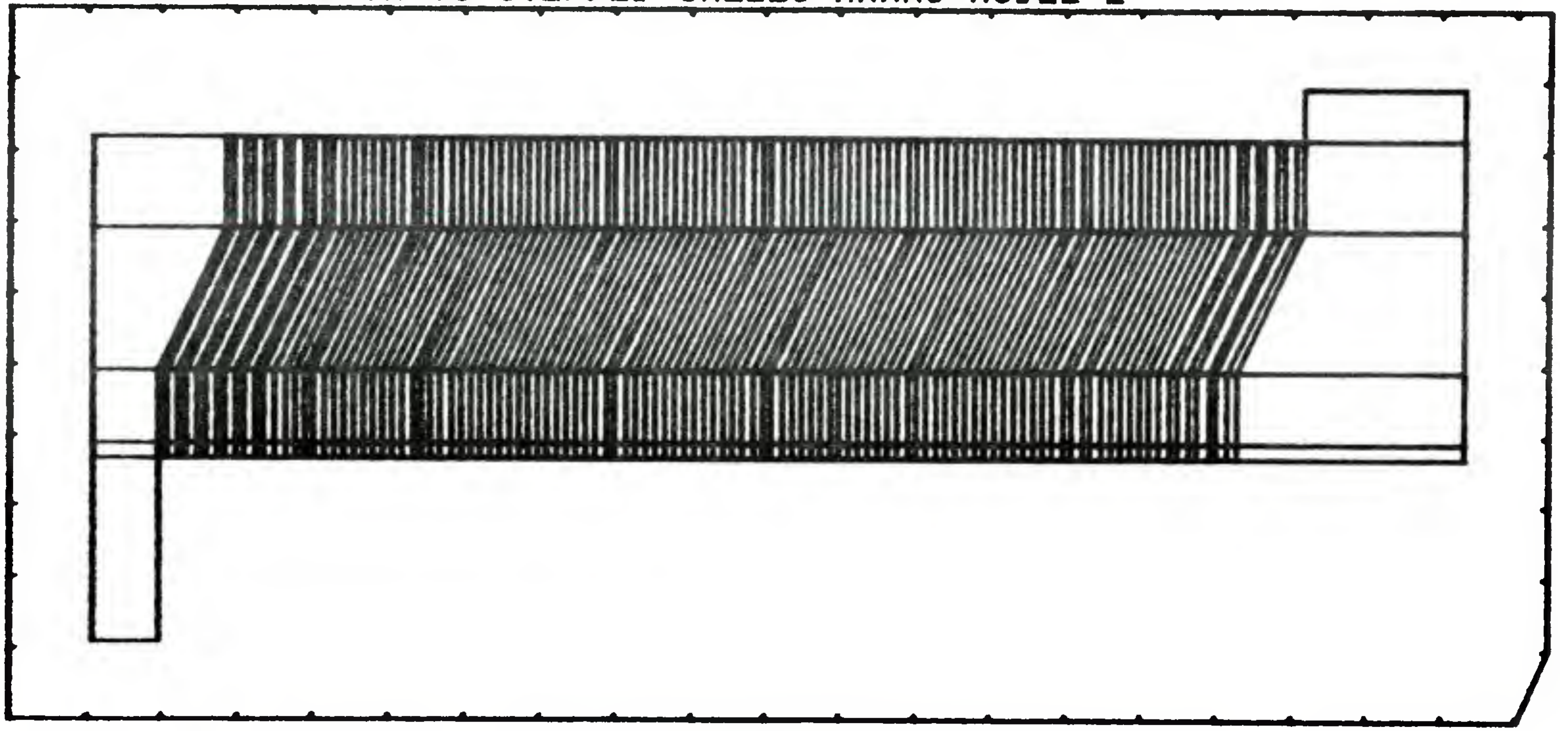
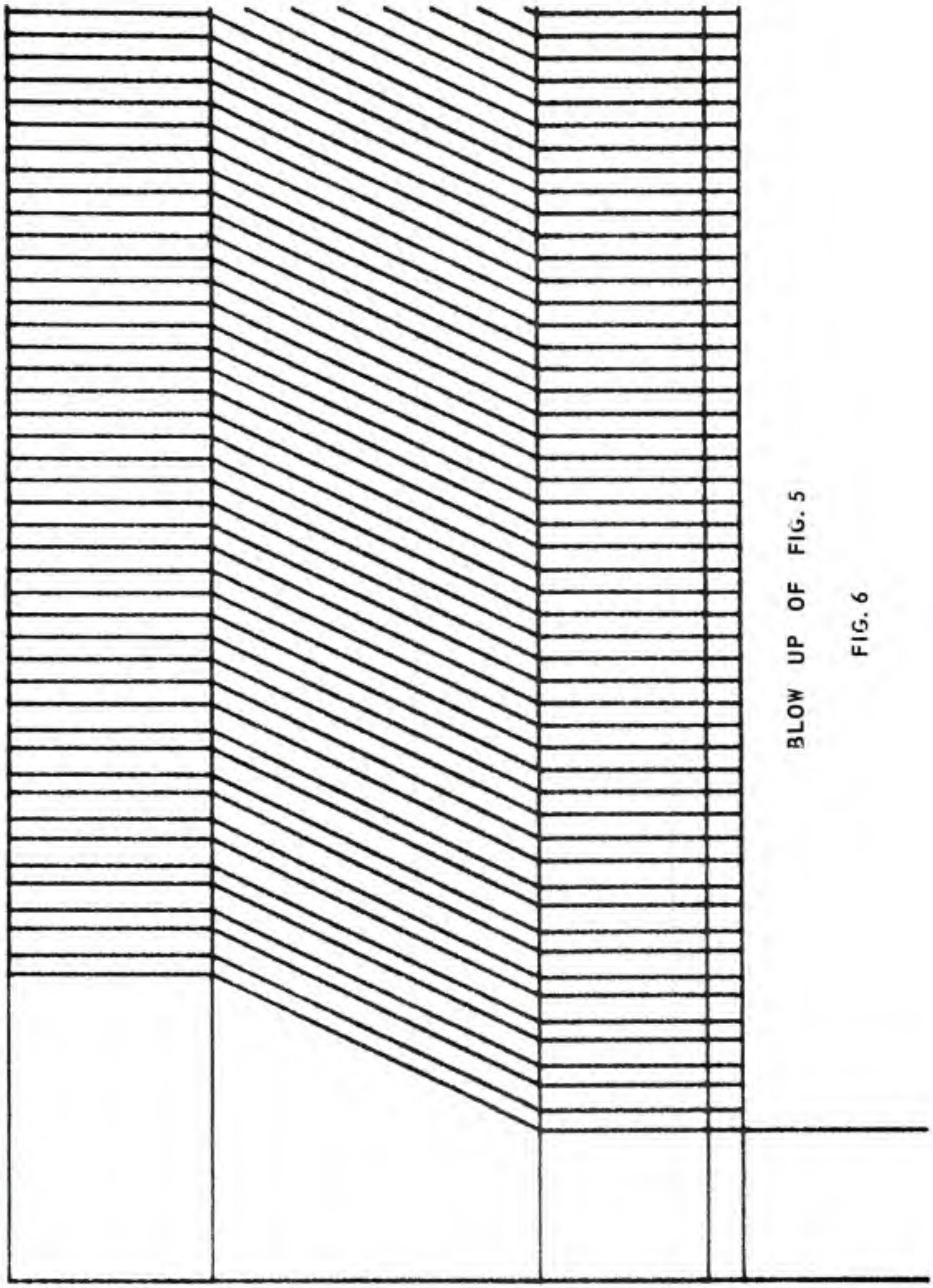


FIG. 5



BLOW UP OF FIG. 5

FIG. 6

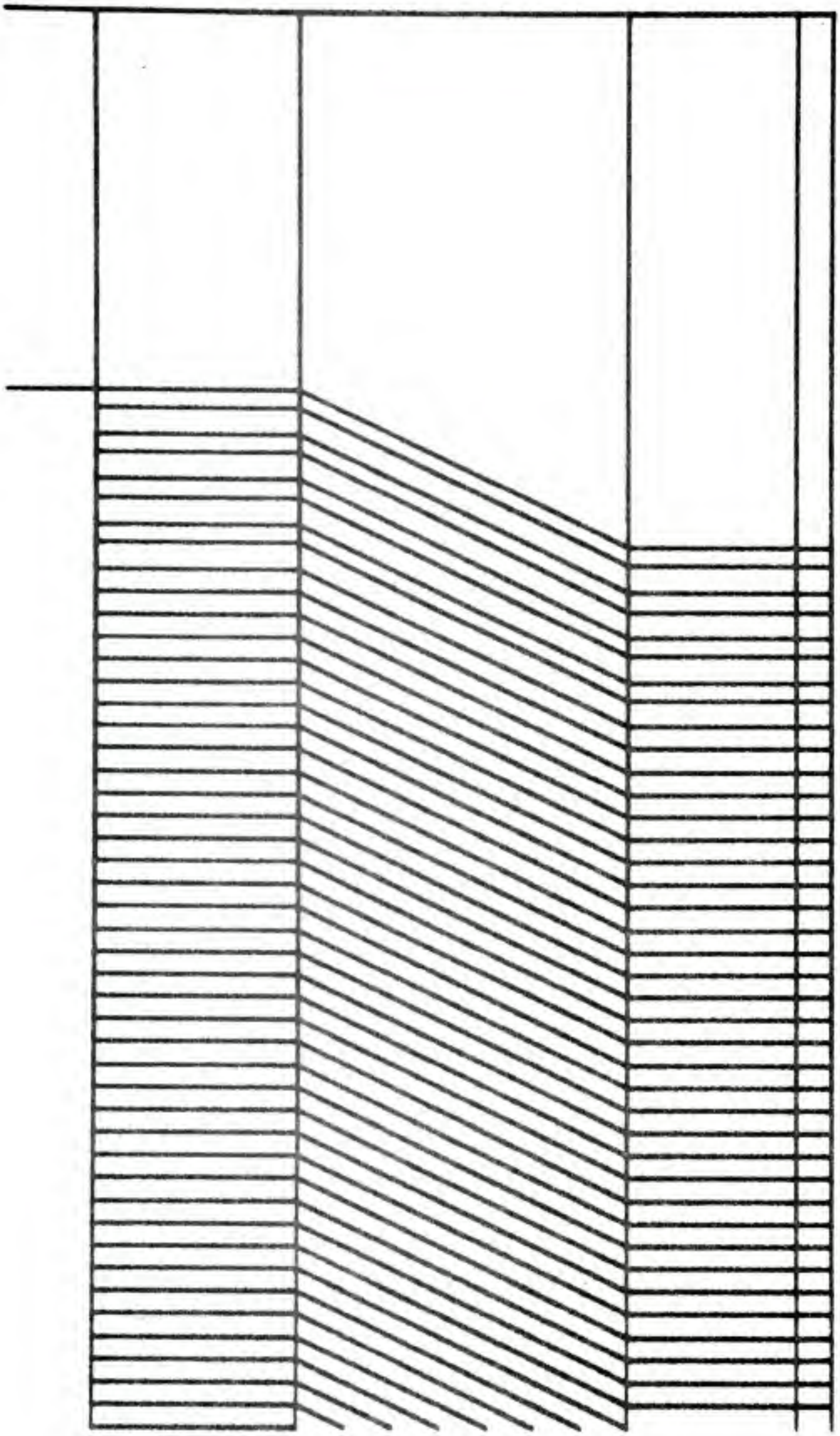
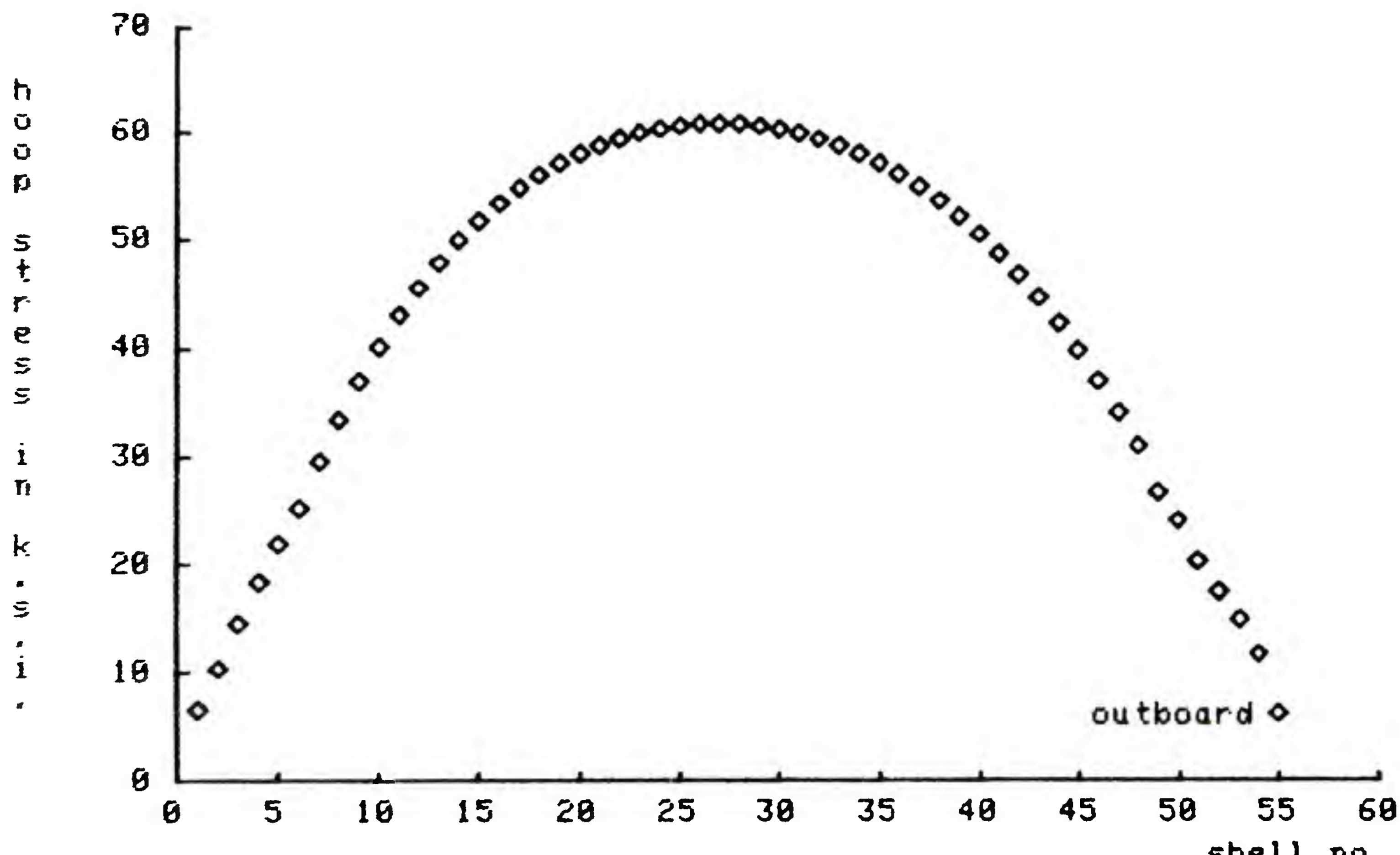


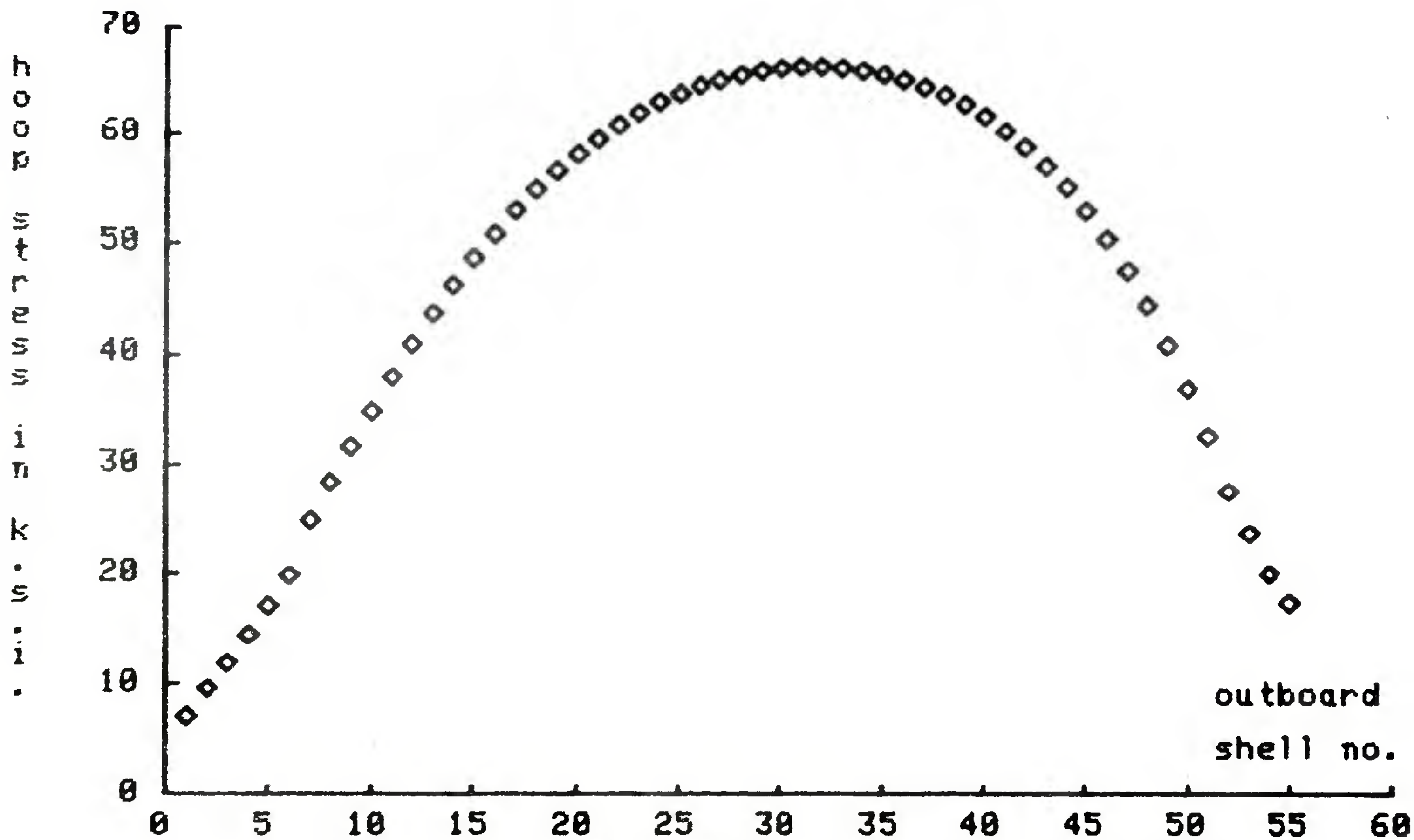
FIG. 7

BLOW UP OF FIG. 5



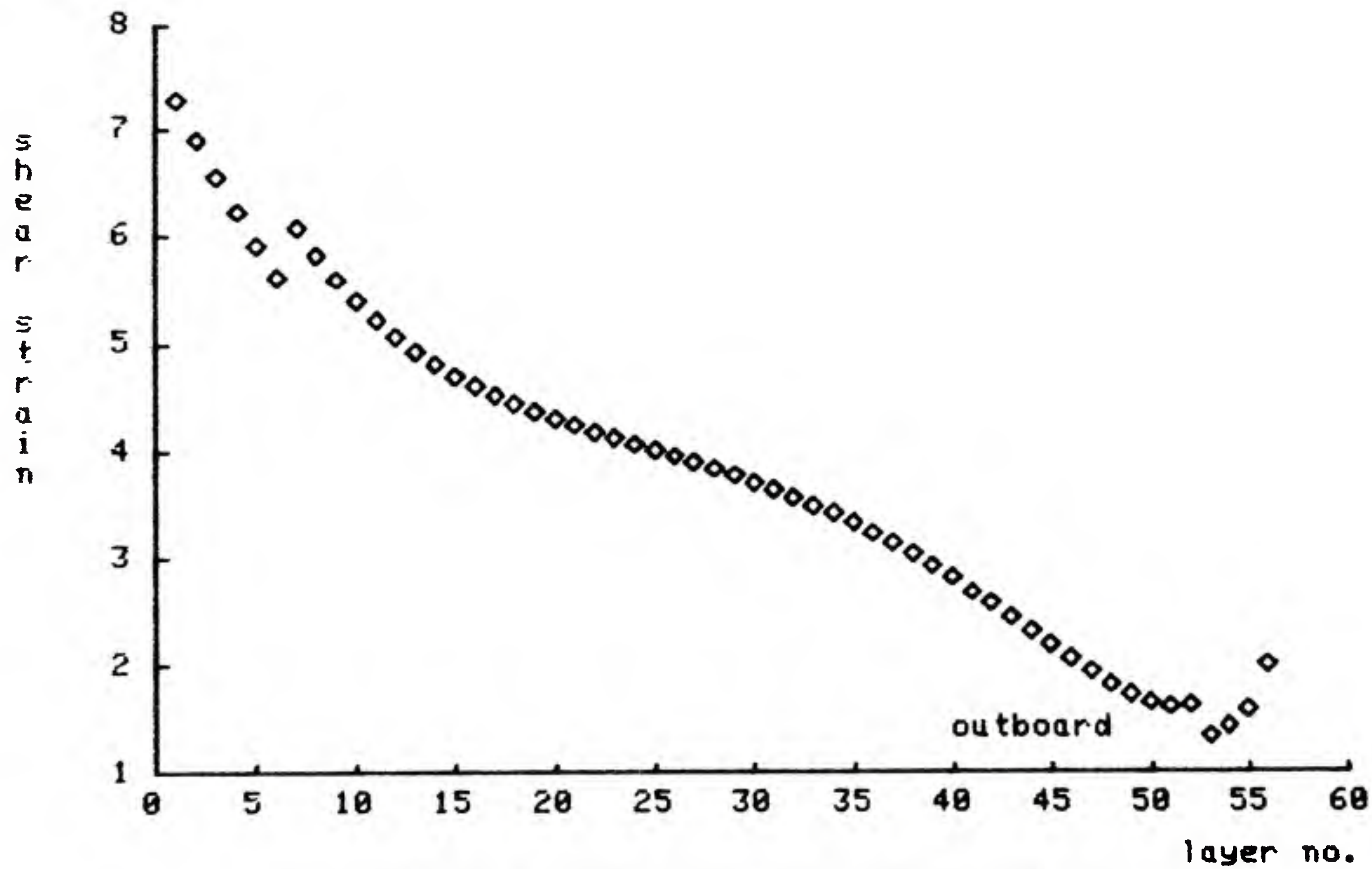
I.D. STRESS @ 68000 LBS. FOR THRUST EB WITH
55 STEPPED SHELLS (AMMRC)
2/2/79

FIG. 8



MAX. STRESS @ 68000 LBS. FOR THRUST EB WITH
55 STEPPED SHELLS (AMMRC)
2/15/79

FIG. 9



I.D. STRAIN @ 68000 LBS. FOR THRUST EB WITH
55 STEPPED SHELLS (AMMRC)
2/16/79

FIG. 10

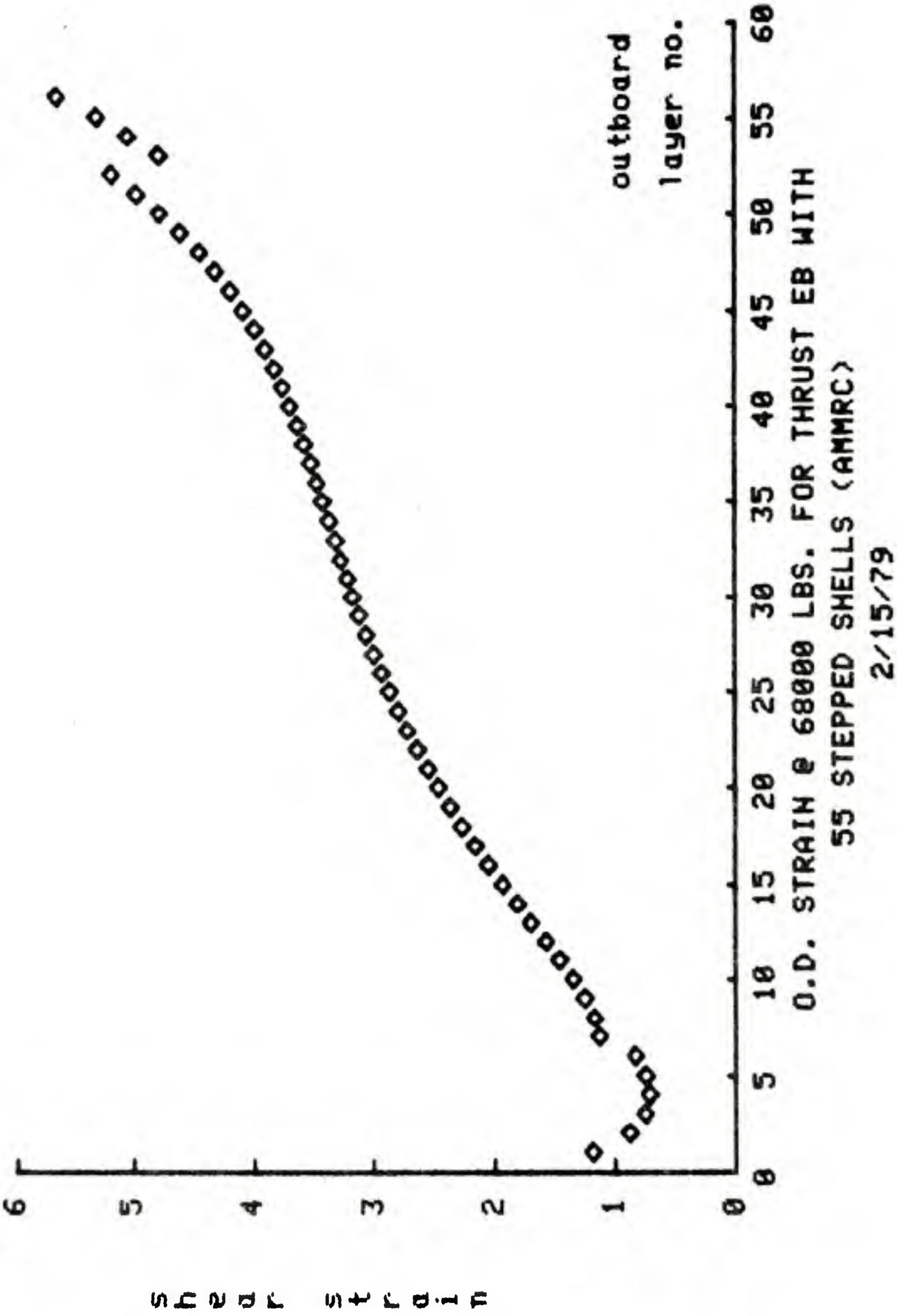

O.D. STRAIN @ 68000 LBS. FOR THRUST EB WITH
55 STEPPED SHELLS (AMMRC)
2/15/79
outboard
layer no.
shear strain
0
5
10
15
20
25
30
35
40
45
50
55
60
0
1
2
3
4
5
6

FIG. 11

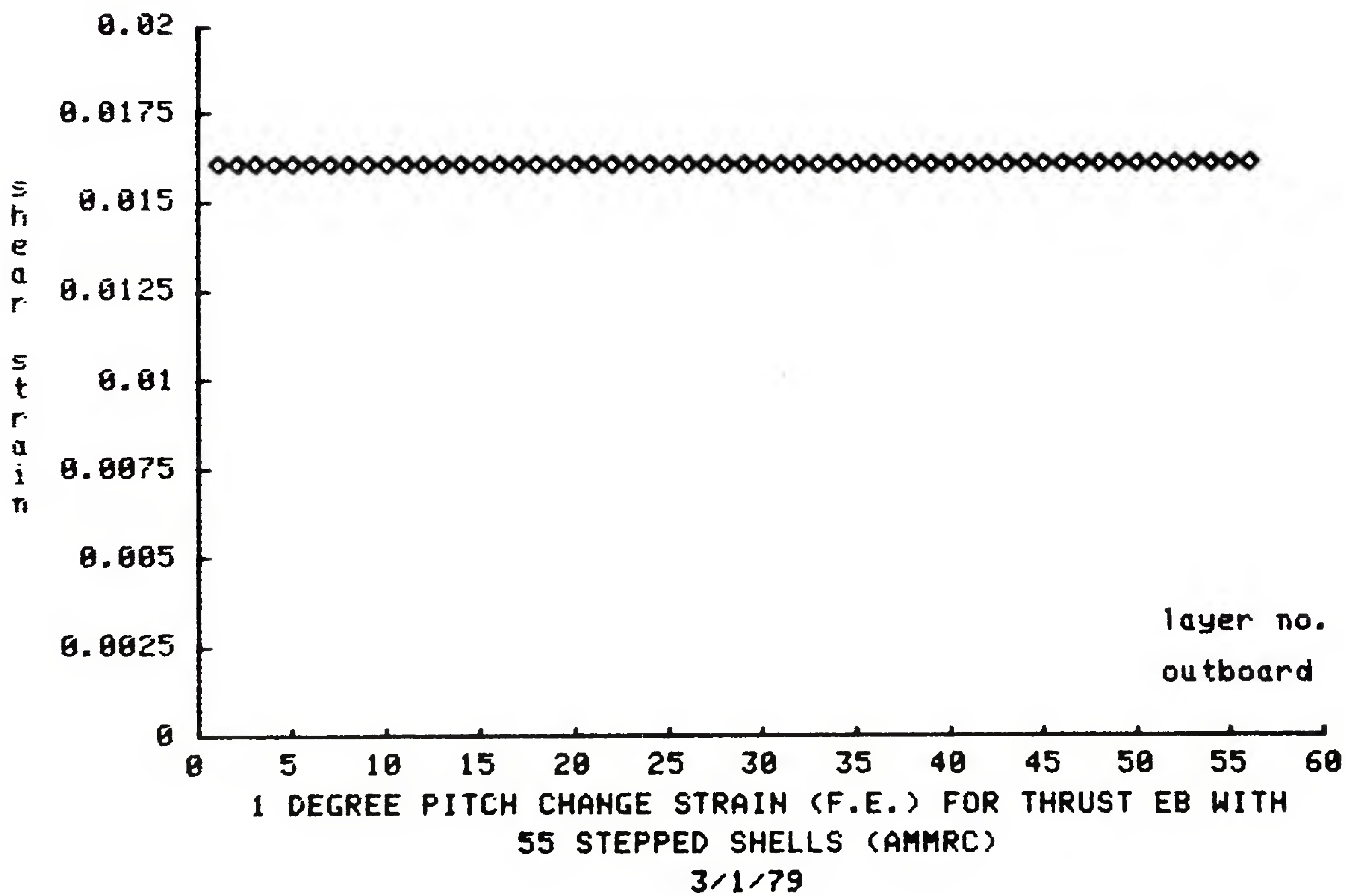
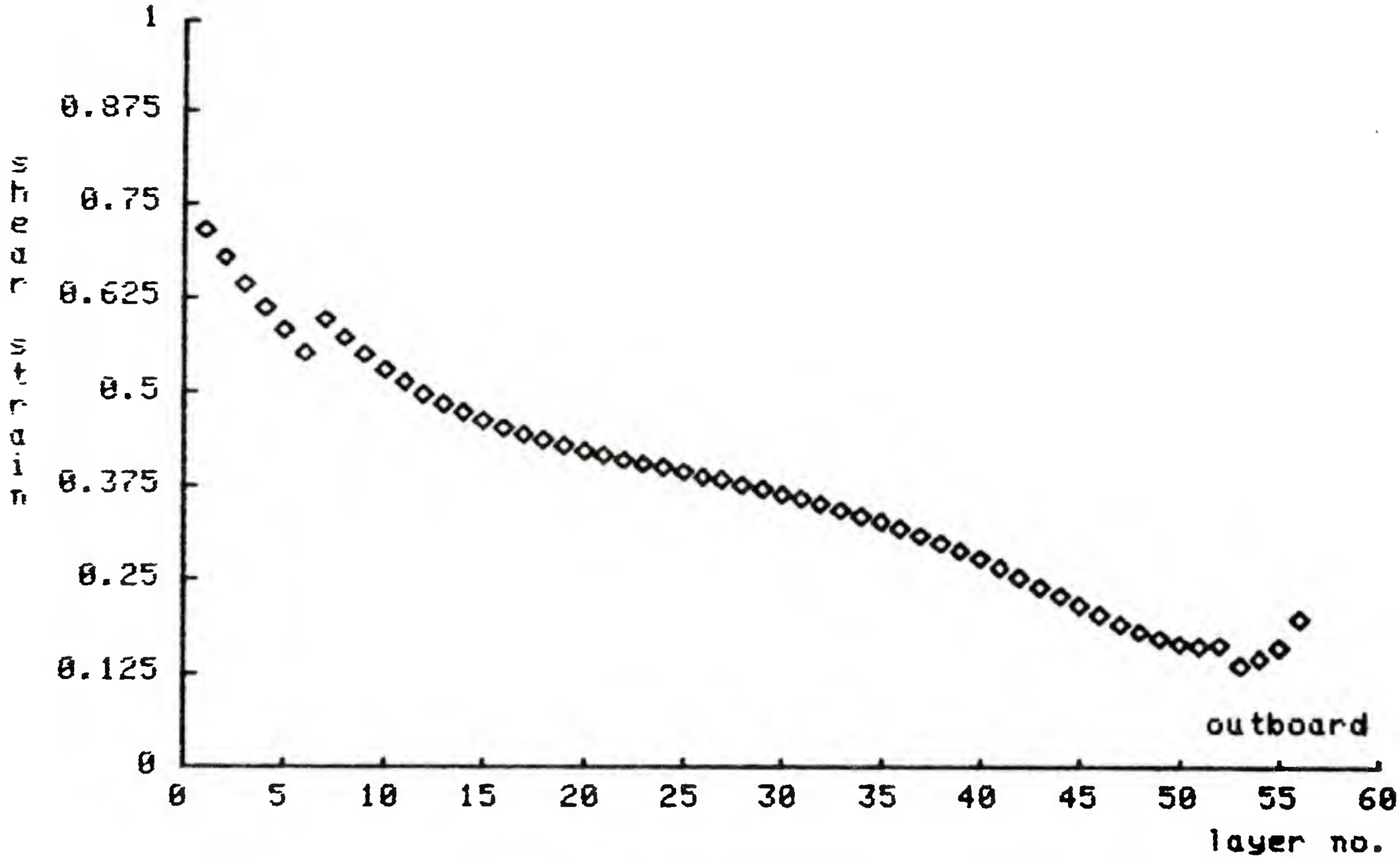
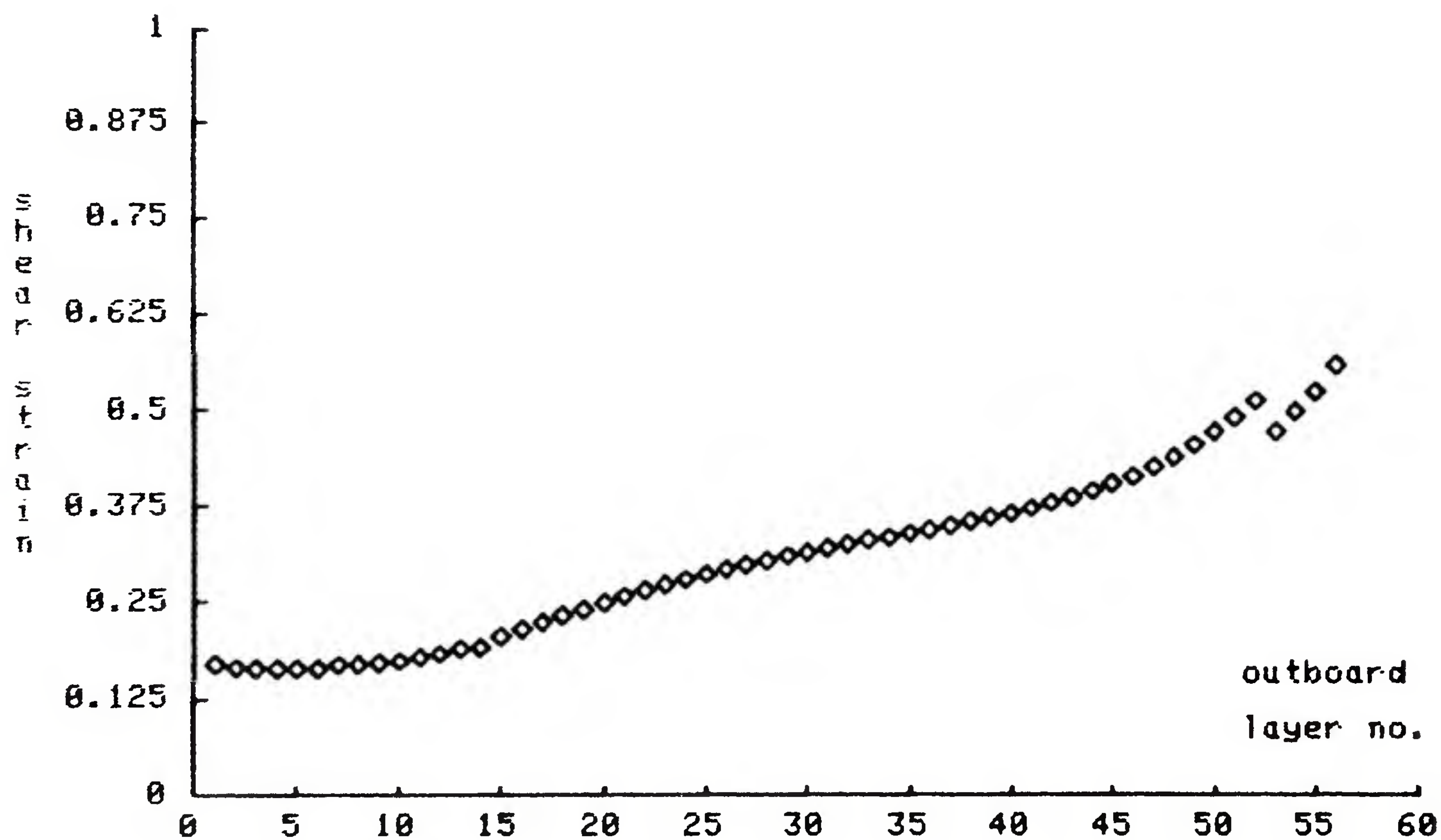

0.02
0.0175
0.015
0.0125
0.01
0.0075
0.005
0.0025
0
shear strain
0
5
10
15
20
25
30
35
40
45
50
55
60
layer no.
outboard
1 DEGREE PITCH CHANGE STRAIN (F.E.) FOR THRUST EB WITH
55 STEPPED SHELLS (AMMRC)
3/1/79

FIG. 12



I.D. LIFE LIMITING STRAIN FOR THRUST EB
WITH 55 STEPPED SHELLS (AMMRC)
2/15/79

FIG. 13



O.D. LIFE LIMITING STRAIN FOR THRUST EB
WITH 55 STEPPED SHELLS (AMMRC)
2/15/79

FIG. 14

A P P E N D I X

```
1:$ THRUST EB WITH 55 STEPPED SHELLS AMMRC MODEL 1
2:SETUP,4,PRESCRIB,10
3:RUBBER,1,600,.4995
4:TITANM,2,15E6,.3
5:TITANM,3,15E6,.3
6:ALUMNM,4,10E6,.33
7:END,MATERIAL
8:1,1,3,2,.2,1,.2,1
9:1.5,1.795,1.795,1.5
10:0,0,.41,.41
11:4,1,5,2
12:2.261,2.550,2.550,2.261
13:0,0,.2,.2
14:5,1,6,2
15:2.55,3.15,3.15,2.55
16:0,0,.2,.2
17:1,3,3,4,.2,1,.2,1
18:1.5,1.795,1.795,1.5
19:.435,.435,.470,.470
20:4,3,5,4
21:2.261,2.550,2.550,2.261
22:.225,.225,.260,.260
23:1,5,3,6,.2,1,.2,1
24:1.5,1.795,1.795,1.5
25:.495,.495,.530,.530
26:4,5,5,6
27:2.261,2.550,2.550,2.261
28:.285,.285,.320,.320
29:1,7,3,8,.2,1,.2,1
30:1.5,1.795,1.795,1.5
31:.555,.555,.590,.590
32:4,7,5,8
33:2.261,2.550,2.550,2.261
34:.345,.345,.380,.380
```

```
35:1,9,3,10,.2,1,.2,1
36:1.5,1.795,1.795,1.5
37:.615,.615,.650,.650
38:4,9,5,10
39:2.261,2.550,2.550,2.261
40:.405,.405,.440,.440
41:1,11,3,12,.2,1,.2,1
42:1.5,1.795,1.795,1.5
43:.675,.675,.710,.710
44:4,11,5,12
45:2.261,2.550,2.550,2.261
46:.465,.465,.500,.500
47:1,13,3,14,.2,1,.2,1
48:1.5,1.795,1.795,1.5
49:.735,.735,.77,.77
50:4,13,5,14
51:2.261,2.550,2.550,2.261
52:.525,.525,.560,.560
53:1,14,3,70,.2,1,.2,1
54:1.5,1.795,1.795,1.5
55:.770,.770,2.450,2.450
56:4,14,5,70
57:2.261,2.550,2.550,2.261
58:.56,.56,2.24,2.24
59:6,30,8,64,.2,1,.2,1
60:1.5,1.795,1.795,1.5
61:2.45,2.45,3.47,3.47
62:9,30,10,64
63:2.261,2.550,2.550,2.261
64:2.24,2.24,3.26,3.26
65:6,65,8,66,.2,1,.2,1
66:1.5,1.795,1.795,1.5
67:3.5,3.5,3.535,3.535
68:9,65,10,66
```

```
69:2.261,2.550,2.550,2.261
70:3.29,3.29,3.325,3.325
71:6,67,8,68,.2,1,.2,1
72:1.5,1.795,1.795,1.5
73:3.56,3.56,3.595,3.595
74:9,67,10,68
75:2.261,2.550,2.550,2.261
76:3.35,3.35,3.385,3.385
77:6,69,8,70,.2,1,.2,1
78:1.5,1.795,1.795,1.5
79:3.62,3.62,3.655,3.655
80:9,69,10,70
81:2.261,2.550,2.550,2.261
82:3.41,3.41,3.445,3.445
83:6,71,8,72,.2,1,.2,1
84:1.5,1.795,1.795,1.5
85:3.680,3.680,3.715,3.715
86:9,71,10,72
87:2.261,2.550,2.550,2.261
88:3.47,3.47,3.505,3.505
89:5,73,6,74
90:1.33,1.5,1.5,1.33
91:3.74,3.74,4.24,4.24
92:6,73,8,74,.2,1,.2,1
93:1.5,1.795,1.795,1.5
94:3.74,3.74,4.24,4.24
95:9,73,10,74
96:2.261,2.55,2.55,2.261
97:3.53,3.53,4.24,4.24
98:END,GRID
99:ILOOP,5,1
100:QUAD,4,1,1
101:IEND
102:ILOOP,4,1
```

```
103:BC,SLOPE,1,1,1
104:IEND
105:JLOOP,33,2
106:ILOOP,4,1
107:QUAD,1,1,2
108:IEND
109:ILOOP,4,1
110:QUAD,2,1,3
111:IEND
112:JEND
113:ILOOP,4,1
114:QUAD,1,1,68
115:IEND
116:ILOOP,4,1
117:QUAD,2,1,69,2,69,7,30,6,30
118:IEND
119:JLOOP,21,2
120:ILOOP,4,1
121:QUAD,1,6,30
122:IEND
123:ILOOP,4,1
124:QUAD,2,6,31
125:IEND
126:JEND
127:ILOOP,4,1
128:QUAD,1,6,72
129:IEND
130:ILOOP,5,1
131:QUAD,3,5,73
132:IEND
133:ILOOP,4,1
135:BC,PRESSURE,6,73,3,5434
136:IEND
137:END,ELEMENTS
```

```
138:PLOT,ELEMENTS,1.08,-.25,3.4,4.49,10
139:AXISYM
140:STOP
```

```
 1:$ THRUST EB WITH 55 STEPPED SHELLS AMMRC MODEL 2
 2:SETUP,4,PRESCRIB,10
 3:RUBBER,1,600,.4995
 4:TITANM,2,15E6,.3
 5:TITANM,3,15E6,.3
 6:ALUMNM,4,10E6,.33
 7:END,MATERIAL
 8:1,1,2,2
 9:1.5,1.795,1.795,1.5
10:0,0,.41,.41
11:3,1,5,2,4.886,1,4.886,1
12:2.261,2.550,2.550,2.261
13:0,0,.2,.2
14:5,1,6,2
15:2.55,3.15,3.15,2.55
16:0,0,.2,.2
17:1,3,2,4
18:1.5,1.795,1.795,1.5
19:.435,.435,.470,.470
20:3,3,5,4,4.886,1,4.886,1
21:2.261,2.550,2.550,2.261
22:.225,.225,.260,.260
23:1,5,2,6
24:1.5,1.795,1.795,1.5
25:.495,.495,.530,.530
26:3,5,5,6,4.886,1,4.886,1
27:2.261,2.550,2.550,2.261
28:.285,.285,.320,.320
29:1,7,2,8
30:1.5,1.795,1.795,1.5
31:.555,.555,.590,.590
32:3,7,5,8,4.886,1,4.886,1
33:2.261,2.550,2.550,2.261
34:.345,.345,.380,.380
```

```
35:1,9,2,10
36:1.5,1.795,1.795,1.5
37:.615,.615,.650,.650
38:3,9,5,10,4.886,1,4.886,1
39:2.261,2.550,2.550,2.261
40:.405,.405,.440,.440
41:1,11,2,12
42:1.5,1.795,1.795,1.5
43:.675,.675,.710,.710
44:3,11,5,12,4.886,1,4.886,1
45:2.261,2.550,2.550,2.261
46:.465,.465,.500,.500
47:1,13,2,14
48:1.5,1.795,1.795,1.5
49:.735,.735,.77,.77
50:3,13,5,14,4.886,1,4.886,1
51:2.261,2.550,2.550,2.261
52:.525,.525,.560,.560
53:1,14,2,70
54:1.5,1.795,1.795,1.5
55:.770,.770,2.450,2.450
56:3,14,5,70,4.886,1,4.886,1
57:2.261,2.550,2.550,2.261
58:.56,.56,2.24,2.24
59:6,30,7,64
60:1.5,1.795,1.795,1.5
61:2.45,2.45,3.47,3.47
62:8,30,10,64,4.886,1,4.886,1
63:2.261,2.550,2.550,2.261
64:2.24,2.24,3.26,3.26
65:6,65,7,66
66:1.5,1.795,1.795,1.5
67:3.5,3.5,3.535,3.535
68:8,65,10,66,4.886,1,4.886,1
```

```
69:2.261,2.550,2.550,2.261
70:3.29,3.29,3.325,3.325
71:6,67,7,68
72:1.5,1.795,1.795,1.5
73:3.56,3.56,3.595,3.595
74:8,67,10,68,4.886,1,4.886,1
75:2.261,2.550,2.550,2.261
76:3.35,3.35,3.385,3.385
77:6,69,7,70
78:1.5,1.795,1.795,1.5
79:3.62,3.62,3.655,3.655
80:8,69,10,70,4.886,1,4.886,1
81:2.261,2.550,2.550,2.261
82:3.41,3.41,3.445,3.445
83:6,71,7,72
84:1.5,1.795,1.795,1.5
85:3.680,3.680,3.715,3.715
86:8,71,10,72,4.886,1,4.886,1
87:2.261,2.550,2.550,2.261
88:3.47,3.47,3.505,3.505
89:5,73,6,74
90:1.33,1.5,1.5,1.33
91:3.74,3.74,4.24,4.24
92:6,73,7,74
93:1.5,1.795,1.795,1.5
94:3.74,3.74,4.24,4.24
95:8,73,10,74,4.886,1,4.886,1
96:2.261,2.55,2.55,2.261
97:3.53,3.53,4.24,4.24
98:END,GRID
99:ILOOP,5,1
100:QUAD,4,1,1
101:IEND
102:ILOOP,4,1
```

```
103:BC,SLOPE,1,1,1
104:IEND
105:JLOOP,33,2
106:ILOOP,4,1
107:QUAD,1,1,2
108:IEND
109:ILOOP,4,1
110:QUAD,2,1,3
111:IEND
112:JEND
113:ILOOP,4,1
114:QUAD,1,1,68
115:IEND
116:ILOOP,4,1
117:QUAD,2,1,69,2,69,7,30,6,30
118:IEND
119:JLOOP,21,2
120:ILOOP,4,1
121:QUAD,1,6,30
122:IEND
123:ILOOP,4,1
124:QUAD,2,6,31
125:IEND
126:JEND
127:ILOOP,4,1
128:QUAD,1,6,72
129:IEND
130:ILOOP,5,1
131:QUAD,3,5,73
132:IEND
133:ILOOP,4,1
134:BC,PRESSURE,6,73,3,5434
135:IEND
136:END,ELEMENTS
```

```
137:PLOT,ELEMENTS,1.08,-.25,3.4,4.49,10
138:AXISYM
139:STOP
```

SECTION 7.

ANALYSIS OF THE SHELL STRESSES IN AN ALTERNATE BLACKHAWK MAIN ROTOR THRUST BEARING

The stress in the metal shells of an alternate Blackhawk main rotor thrust bearing (see SK4-80 9590 in Fig. 1) will be analyzed in this section. This analysis can be accomplished with a single finite element problem run without the use of superposition.

The analysis of this thrust bearing begins with the model shown in Figure 2. Even with the coarse modeling technique previously developed, computational limits on the number of available elements prevent a generous representation of the shell radii at the center of the shell where the peak stress occurs. This limitation also restricts the number of shells modeled to 35 -- the real bearing has 52. A small element (see the enlarged view in Figure 3.) is used to check the stress at the transition point in this model. Figure 4 shows the stress that results in this element for a 68,000 pound thrust load.

As a result of the nice plateau on the previous result, the number of shells was further reduced to 17 to study the effect of length on shell stress. The model is shown in Figure 5, a blowup in Figure 6 and the results in Figure 7. The model shown in Figure 8 again has 17 shells but, has a good representation of the center radius. The stress values are shown in Figure 9.

The similarity of Figure 7 and Figure 9 would indicate

that the crude radius representation is giving useful results. The increase in peak stress from Figure 7 to Figure 4, representing an increase from 17 to 35 shells, would suggest an estimate of 115 ksi for the peak stress in the real bearing with 52 shells. In the interest of weight reduction it is intended that the shells for the test bearing be made of A-70 C.P. Titanium. The stress results from the application of the C.F. load should be nonreversing and, hence, it is anticipated that the first loading cycle will locally yield the 70 ksi yield strength titanium so that the stress for subsequent cycles might be considered to be 12.5 $\pm$ 57.5 ksi. Fatigue failure of this part is, therefore, predicted at a reasonably low number of cycles. In service the loading spectrum is somewhat more complicated but, the total number of cycles expected is less than 20,000.

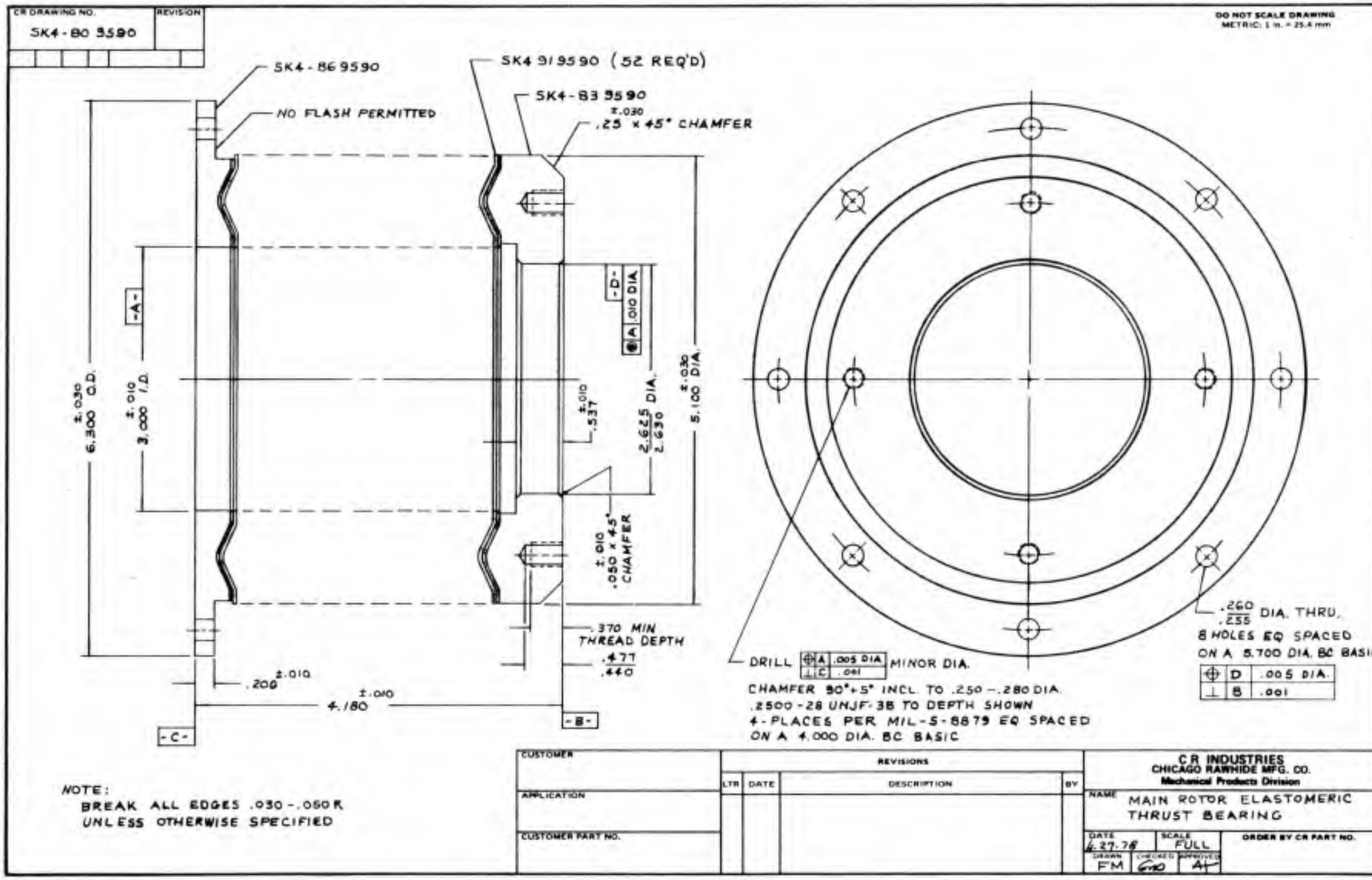

CR DRAWING NO.
SK4-80 9590
REVISION
DO NOT SCALE DRAWING
METRIC: 1 in. = 25.4 mm
SK4-86 9590
NO FLASH PERMITTED
SK4 919590 (52 REQ'D)
SK4-83 9590
±.030
.25 × 45° CHAMFER
±.030
6.300 O.D.
±.010
3.000 I.D.
-A-
-D-
.010 DIA
±.010
.537
2.625
2.630 DIA.
±.030
5.100 DIA.
±.010
.050 × 45°
CHAMFER
.370 MIN
THREAD DEPTH
.477
.440
±.010
.200
±.010
4.180
-B-
-C-
.260
.255 DIA. THRU.
8 HOLES EQ SPACED
ON A 5.700 DIA. BC BASIC
D .005 DIA.
B .001
DRILL A .005 DIA C .001 MINOR DIA.
CHAMFER 90°+5° INCL. TO .250 –.280 DIA.
.2500-28 UNJF-3B TO DEPTH SHOWN
4-PLACES PER MIL-S-8879 EQ SPACED
ON A 4.000 DIA. BC BASIC
NOTE:
BREAK ALL EDGES .030-.050 R
UNLESS OTHERWISE SPECIFIED
CUSTOMER
APPLICATION
CUSTOMER PART NO.
REVISIONS
LTR
DATE
DESCRIPTION
BY
C R INDUSTRIES
CHICAGO RAWHIDE MFG. CO.
Mechanical Products Division
NAME
MAIN ROTOR ELASTOMERIC
THRUST BEARING
DATE
4-27-78
SCALE
FULL
ORDER BY CR PART NO.
DRAWN
FM

FIG. 1

METAL FATIGUE THRUST EB AMMRC MODEL 1

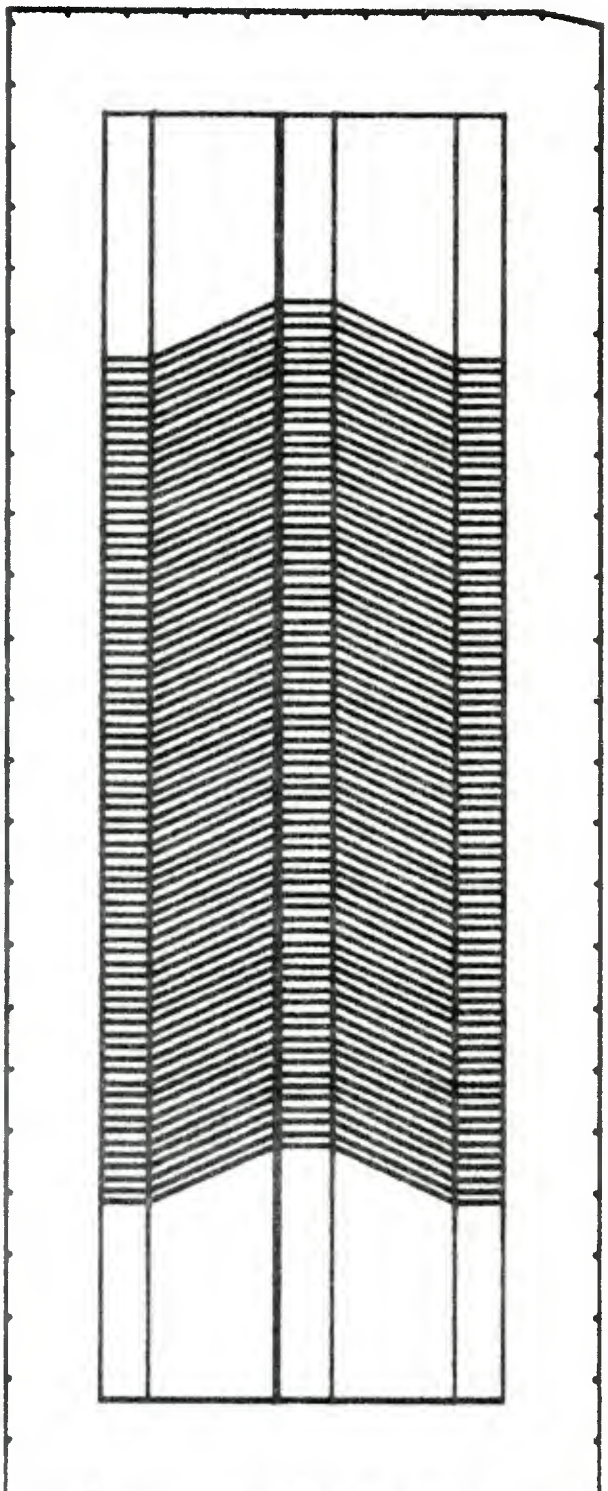
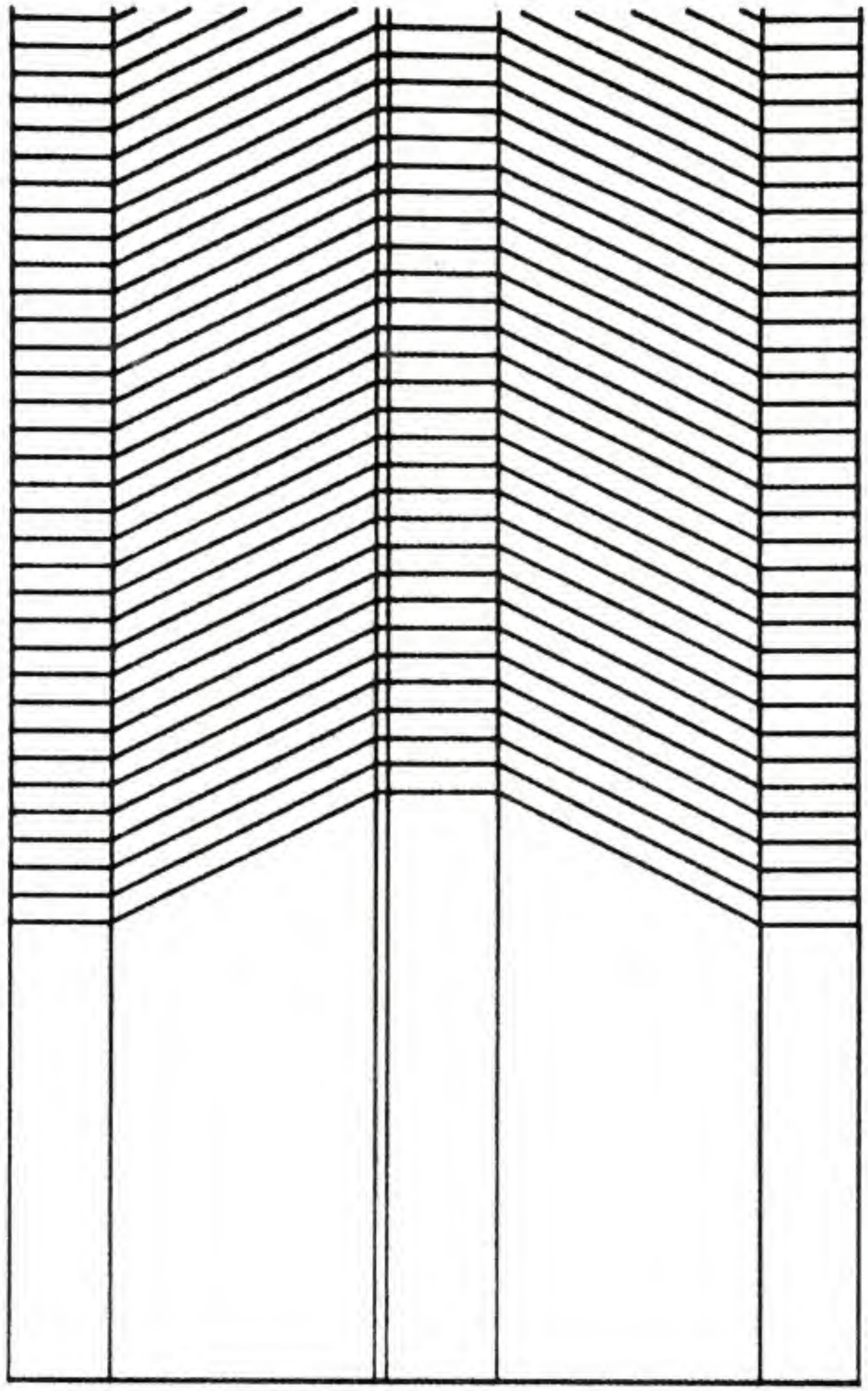
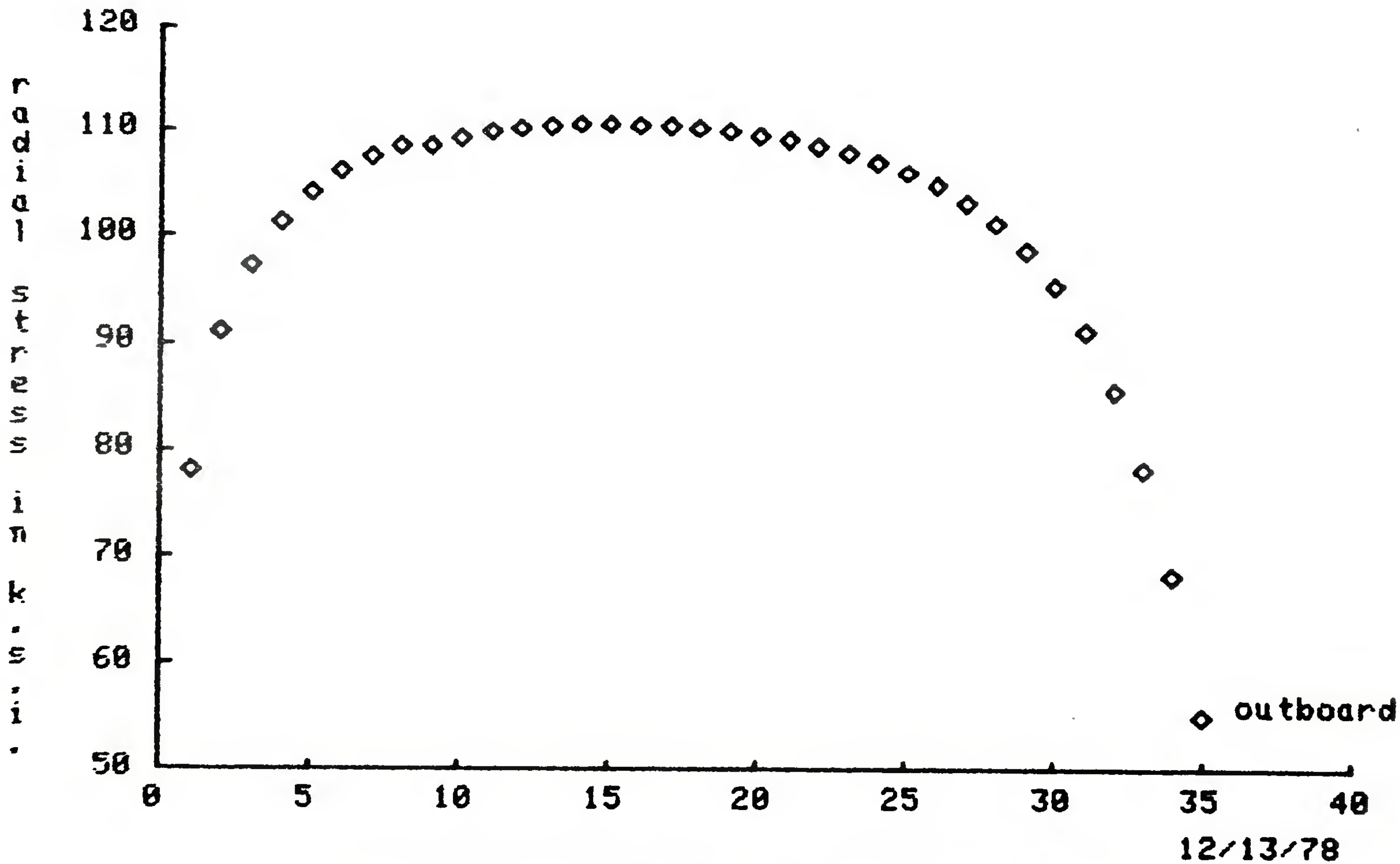


FIG. 2



BLOW UP OF FIG. 2

FIG. 3



SHELL STRESS FOR AMMRC THRUST EB MODEL 1

FIG. 4

METAL FATIGUE THRUST EB AMMRC MODEL 2

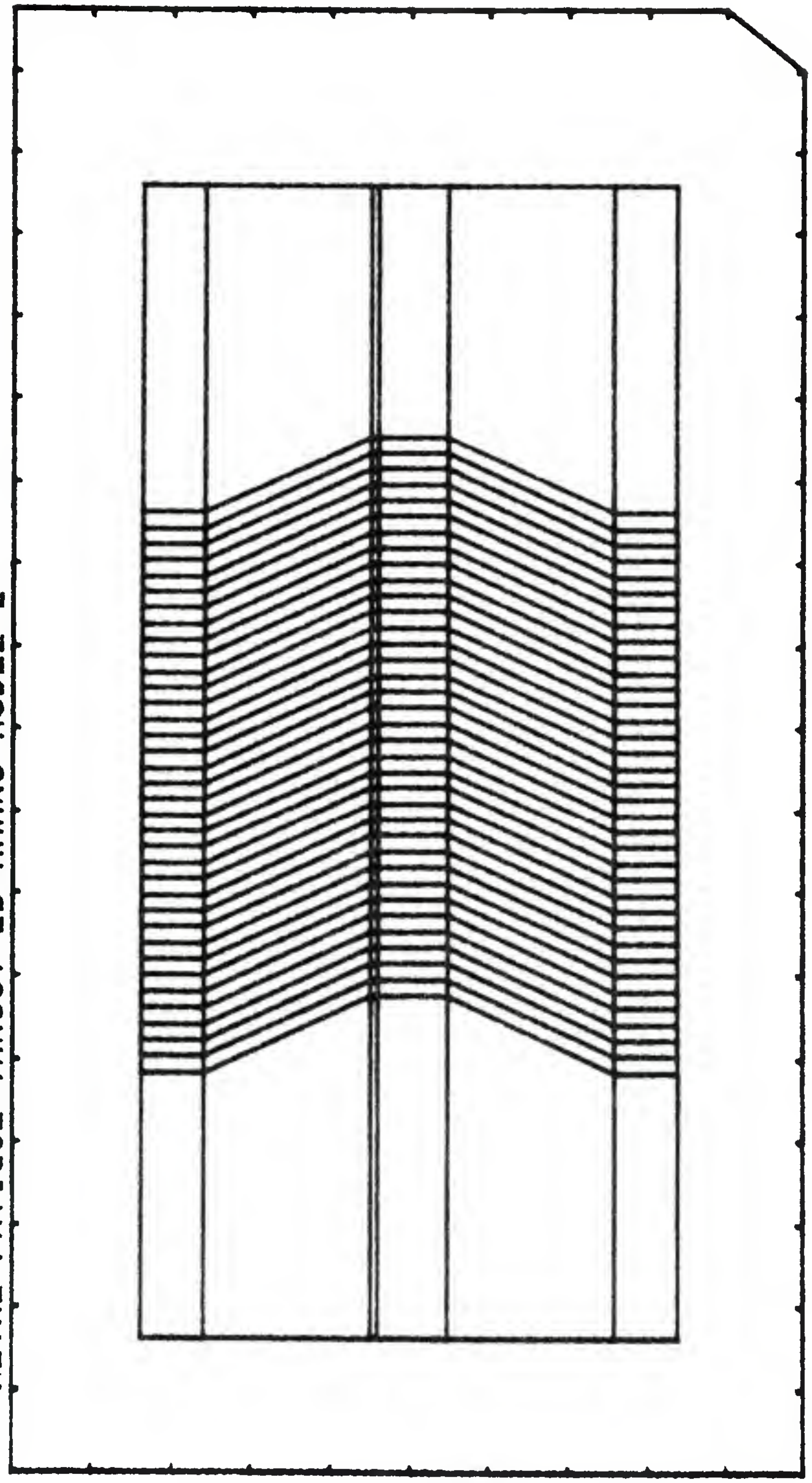
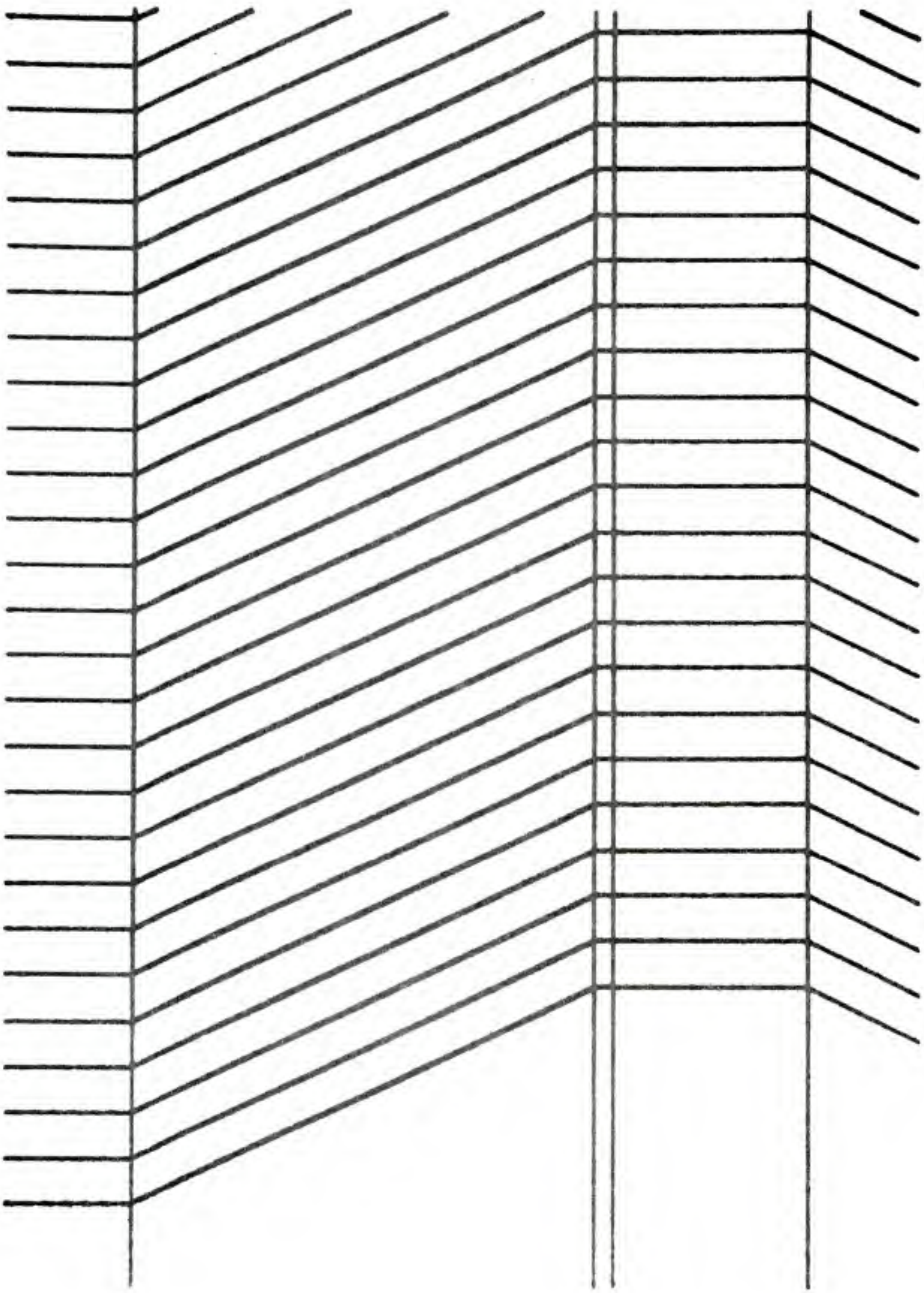
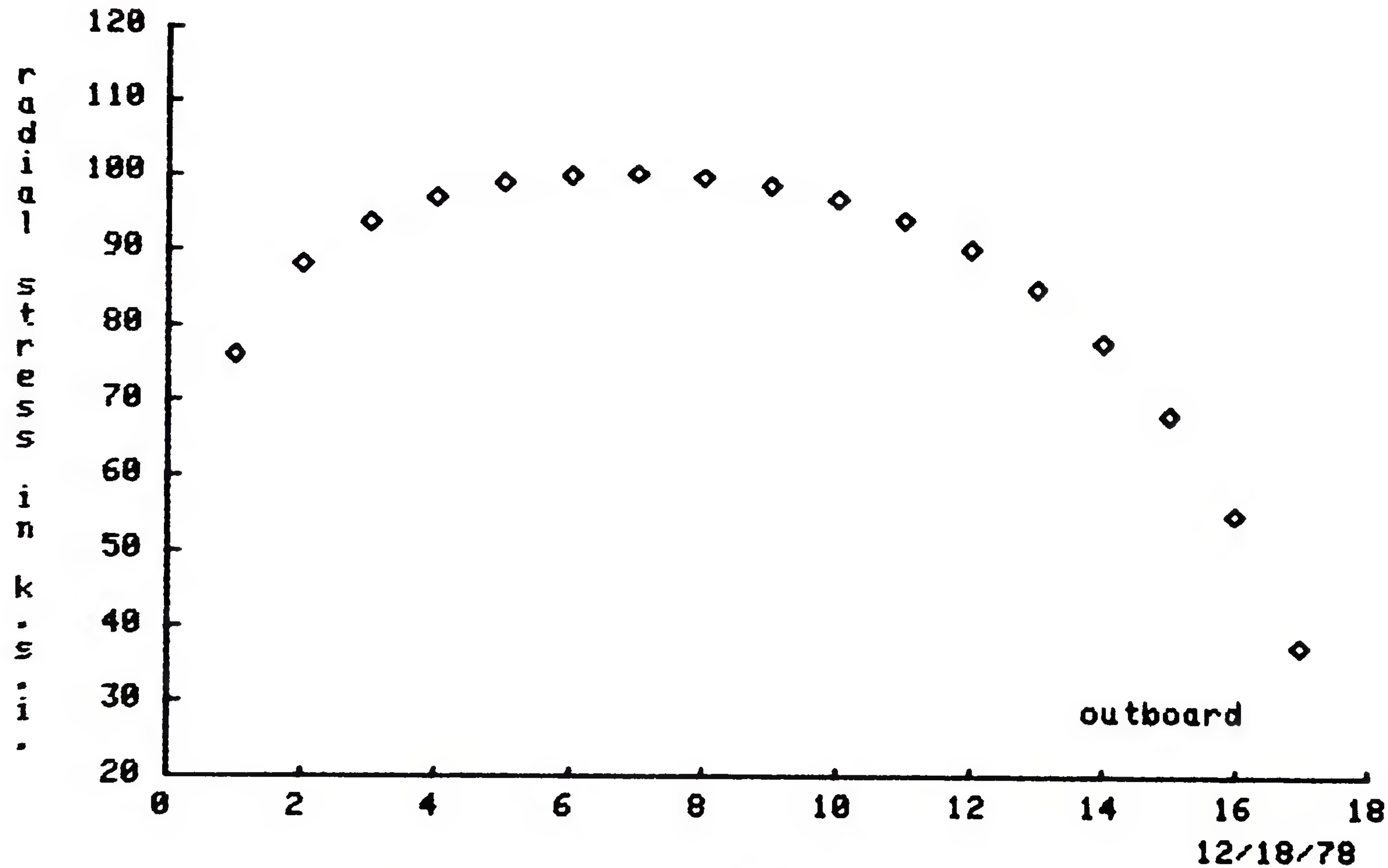


FIG. 5



BLOW UP OF FIG. 5

FIG. 6



SHELL STRESS FOR AMMRC THRUST EB MODEL 2

FIG. 7

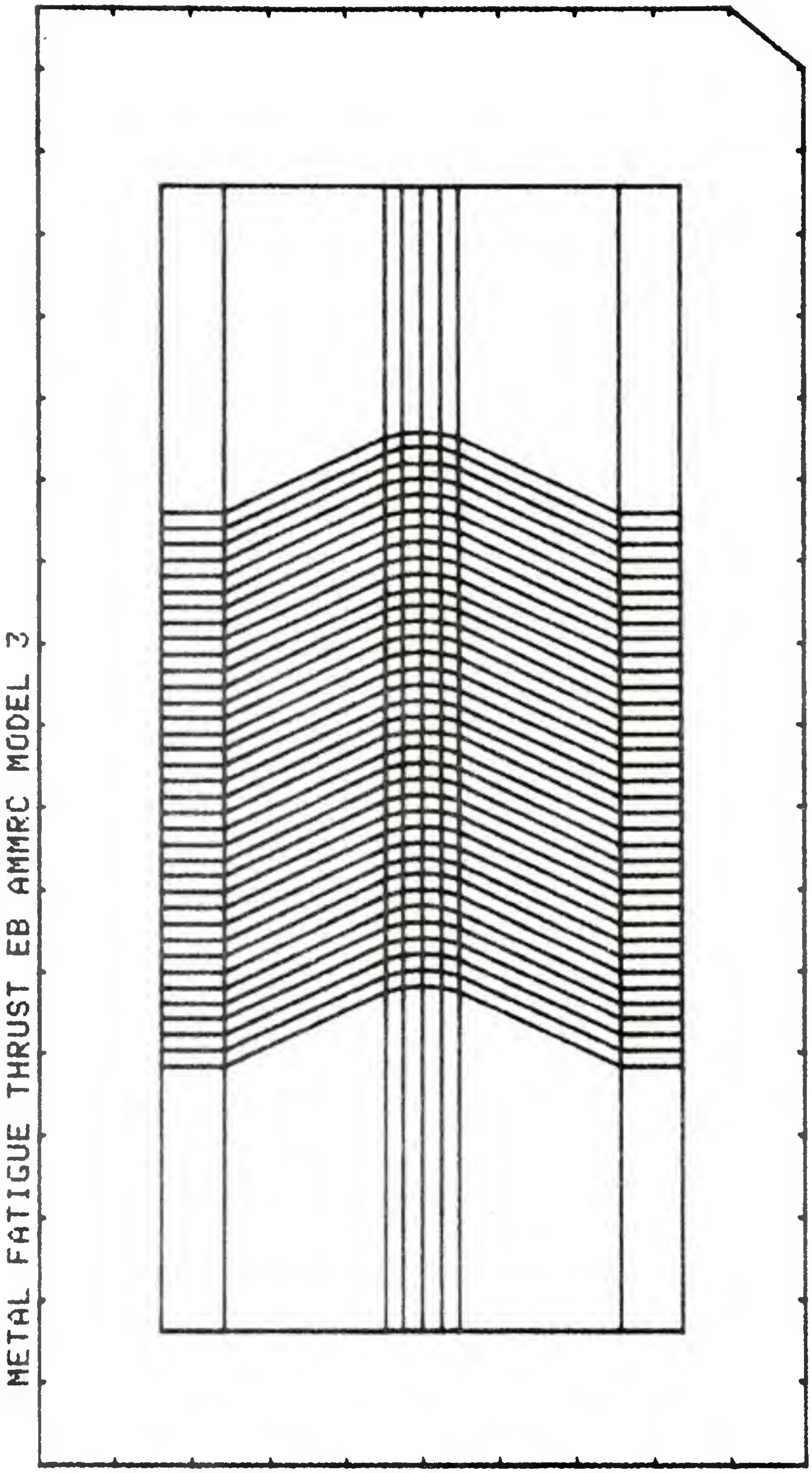
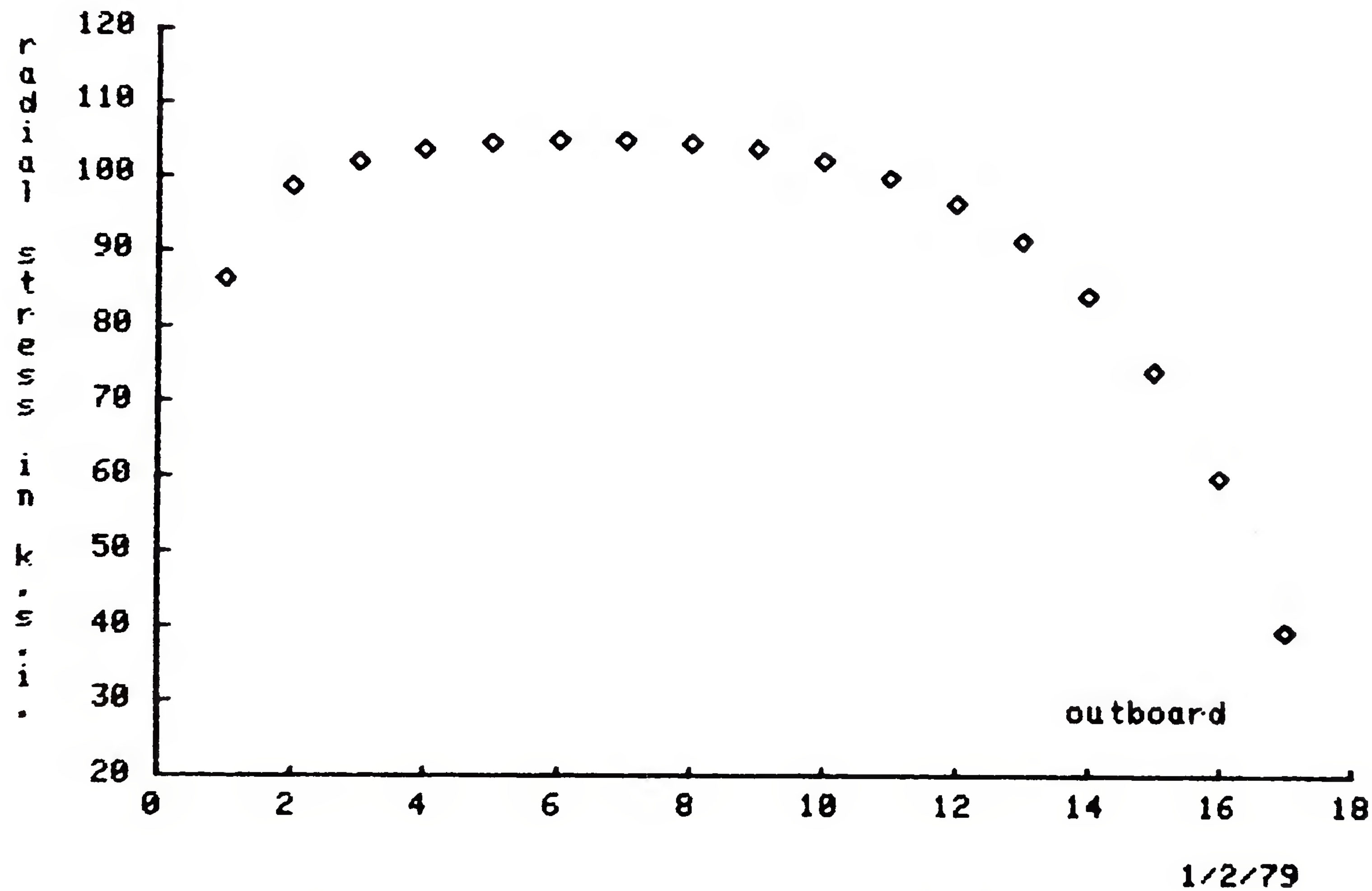


FIG. 8



SHELL STRESS FOR AMMRC THRUST EB MODEL 3

FIG. 9

A P P E N D I X   I

```
 1:$ METAL FATIGUE THRUST EB AMMRC MODEL 1
 2:SETUP,4, ,7
 3:RUBBER,1,600,.4995
 4:STEEL,2,30E6,.3
 5:TITANM,3,15E6,.3
 6:END,MATERIAL
 7:1,1,2,2
 8:1.5,1.625,1.625,1.5
 9:0,0,.5,.5
10:3,1,5,2,.1,1,.1,1
11:1.95,2.1,2.1,1.95
12:0,0,.644,.644
13:6,1,7,2
14:2.425,2.55,2.55,2.425
15:0,0,.5,.5
16:1,2,2,73
17:1.5,1.625,1.625,1.5
18:.5,.5,2.63,2.63
19:3,2,5,73,.1,1,.1,1
20:1.95,2.1,2.1,1.95
21:.644,.644,2.774,2.774
22:6,2,7,73
23:2.425,2.55,2.55,2.425
24:.5,.5,2.63,2.63
25:1,73,2,74
26:1.5,1.625,1.625,1.5
27:2.63,2.63,3.25,3.25
28:3,73,5,74,.1,1,.1,1
29:1.95,2.1,2.1,1.95
30:2.774,2.774,3.25,3.25
```

```
31:6,73,7,74
32:2.425,2.55,2.55,2.425
33:2.63,2.63,3.25,3.25
34:END,GRID
35:ILOOP,6,1
36:QUAD,3,1,1
37:QUAD,1,1,2
38:JLOOP,35,2
39:QUAD,2,1,3
40:QUAD,1,1,4
41:JEND
42:QUAD,3,1,73
43:IEND
44:ILOOP,6,1
45:BC,SLOPE,1,1,1
46:BC,PRESSURE,1,73,3,5434
47:IEND
48:END,ELEMENTS
49:PLOT,ELEMENTS,1.25,-.25,2.8,3.5,10
50:AXISYM
51:STOP
```

A P P E N D I X II

```
 1:$ METAL FATIGUE THRUST EB AMMRC MODEL 2
 2:SETUP,4, ,7
 3:RUBBER,1,600,.4995
 4:STEEL,2,30E6,.3
 5:TITANM,3,15E6,.3
 6:END,MATERIAL
 7:1,1,2,2
 8:1.5,1.625,1.625,1.5
 9:0,0,.5,.5
10:3,1,5,2,.1,1,.1,1
11:1.95,2.1,2.1,1.95
12:0,0,.644,.644
13:6,1,7,2
14:2.425,2.55,2.55,2.425
15:0,0,.5,.5
16:1,2,2,37
17:1.5,1.625,1.625,1.5
18:.5,.5,1.55,1.55
19:3,2,5,37,.1,1,.1,1
20:1.95,2.1,2.1,1.95
21:.644,.644,1.694,1.694
22:6,2,7,37
23:2.425,2.55,2.55,2.425
24:.5,.5,1.55,1.55
25:1,37,2,38
26:1.5,1.625,1.625,1.5
27:1.55,1.55,2.17,2.17
28:3,37,5,38,.1,1,.1,1
29:1.95,2.1,2.1,1.95
30:1.694,1.694,2.170,2.170
31:6,37,7,38
32:2.425,2.55,2.55,2.425
33:1.55,1.55,2.17,2.17
34:END,GRID
```

```
35:ILOOP,6,1
36:QUAD,3,1,1
37:QUAD,1,1,2
38:JLOOP,17,2
39:QUAD,2,1,3
40:QUAD,1,1,4
41:JEND
42:QUAD,3,1,37
43:IEND
44:ILOOP,6,1
45:BC,SLOPE,1,1,1
46:BC,PRESSURE,1,37,3,5434
47:IEND
48:END,ELEMENTS
49:PLOT,ELEMENTS,1.25,-.25,2.8,2.5,10
50:AXISYM
51:STOP
```

A P P E N D I X III

```
1:$ METAL FATIGUE THRUST EB AMMRC MODEL 3
2:SETUP,4, ,10
3:RUBBER,1,600,.4995
4:STEEL,2,30E6,.3
5:TITANM,3,15E6,.3
6:END,MATERIAL
7:1,1,2,2
8:1.5,1.625,1.625,1.5
9:0,0,.5,.5
10:3,1,4,2
11:1.95,1.9875,1.9875,1.95
12:0,0,.6527,.644
13:5,1,5,2
14:2.025,2.025,2.025,2.025
15:0,0,.6555,.6555
16:6,1,7,2
17:2.0625,2.1,2.1,2.0625
18:0,0,.644,.6527
19:8,1,9,2
20:2.425,2.55,2.55,2.425
21:0,0,.5,.5
22:1,2,2,37
23:1.5,1.625,1.625,1.5
24:.5,.5,1.55,1.55
25:3,2,4,37
26:1.95,1.9875,1.9875,1.95
27:.644,.6527,1.7027,1.694
28:5,2,5,37
29:2.025,2.025,2.025,2.025
30:.655,.655,1.7055,1.7055
31:6,2,7,37
32:2.0625,2.1,2.1,2.0625
33:.6527,.644,1.694,1.7027
```

```
34:8,2,9,37
35:2.425,2.55,2.55,2.425
36:.5,.5,1.55,1.55
37:1,37,2,38
38:1.5,1.625,1.625,1.5
39:1.55,1.55,2.17,2.17
40:3,37,4,38
41:1.95,1.9875,1.9875,1.95
42:1.694,1.7027,2.17,2.17
43:5,37,5,38
44:2.025,2.025,2.025,2.025
45:1.7055,1.7055,2.17,2.17
46:6,37,7,38
47:2.0625,2.1,2.1,2.0625
48:1.7027,1.694,2.17,2.17
49:8,37,9,38
50:2.425,2.55,2.55,2.425
51:1.55,1.55,2.17,2.17
52:END,GRID
53:ILOOP,8,1
54:QUAD,3,1,1
55:QUAD,1,1,2
56:JLOOP,17,2
57:QUAD,2,1,3
58:QUAD,1,1,4
59:JEND
60:QUAD,3,1,37
61:IEND
62:ILOOP,8,1
63:BC,SLOPE,1,1,1
64:BC,PRESSURE,1,37,3,5434
65:IEND
66:END,ELEMENTS
```

```
67:PLOT,ELEMENTS,1.25,-.25,2.8,2.5,10
68:AXISYM
69:STOP
```

SECTION 8.

ANALYSIS OF THE BLACKHAWK MAIN ROTOR SPHERICAL BEARING

The subject covered in this section is an analysis of the elastomer strain in the Blackhawk main rotor spherical elastomeric bearing (see Figure 1) and a prediction of the life of this bearing. It is suggested that the two sections, covering finite element analysis and determining the life of elastomeric parts based on strain, be reviewed.

The model for the spherical bearing is shown in Figure 2 and an enlargement in Figure 3. A listing of the input program is shown in Appendix I. In order to generate the nodal data for this program a mesh generator program was written in Basic language for our Tektronix 4051 mini-computer. This program is included in Appendix II.

The strain resulting from a 68,000 pound axial C.F. load is shown for the I.D. in Figure 4 and for the O.D. in Figure 5. At the 6 and 12 o'clock positions the strain for an out-of-plane load of 1,292 pounds is shown in Figure 6 for the I.D. and Figure 7 for the O.D.. For this load at the 3 and 9 o'clock positions the strain at the I.D. is shown in Figure 8 and for the O.D. in Figure 9. The strain at the 6 and 12 o'clock position for a 1 degree flapping cock is shown in Figure 10 for the I.D. and Figure 11 for the O.D. The 3 and 9 o'clock strains are shown in Figures 12 and 13.

The strain due to pitch change may be calculated directly from first principals. The relationships are derived in Appendix III and a Basic language computer program is listed in Appendix IV. The calculated I.D. strain for 1 degree of pitch change rotation is given in Figure 14. The finite element solution is shown in Figure 15. It can be seen that at the I.D. the agreement is very good. At the O.D. there is an approximate 10% difference. The O.D. finite element results are given in Figure 16. The spherical and the thrust bearing share the total pitch change motion.

Spring rate of the spherical bearing 1000 in-lbs./degree.

Spring rate of the thrust bearing 120 in-lbs./degree.

$$\left(\frac{120}{1000 + 120}\right) 100 = 10.7\% \text{ of the pitch change for the spherical bearing.}$$

The following is a sample calculation of the life limiting strain for the 6 and 12 o'clock position on the I.D. of the fourth layer:

The vibratory strain vectors due to flap ($\pm\ \Theta_x$), inplane load ($\pm\ V_c$) and vibratory out-of-plane load ($\pm\ V_n$) are all in the same direction and phase. The strain magnitudes are, therefore, directly additive.

$$\gamma_{v_1} = 3.58*0.0803 + 2.984 * \left(\frac{315}{68000}\right) + 0.0777$$

$$\gamma_{v_1} = 0.379$$

Note: Pitch change strain did not enter the above calculation because it is 90° out of phase in both geometry and time but, its Miner's Rule effect will be considered in the following vector:

$$\gamma_{v2} = 0.0385*6.54*0.107 = 0.0269$$

The life limiting strain is (see Appendix of Section 3)

$$\gamma = \sqrt[5]{\frac{258*60\left[\gamma_{v_1}{}^5 + \gamma_{v_2}{}^5\right] + \left(\frac{\gamma_{cf}}{2} * \frac{82000}{68000}\right)^5 + 2*\left(\frac{\gamma_{cf}}{2}\right)^5}{258*60 + 1 + 2}}$$

$$\gamma = \sqrt[5]{\frac{258*60(.379^5 + .0269^5) + \left(\frac{2.984}{2}\frac{*82000}{68000}\right)^5 + 2*\left(\frac{2.984}{2}\right)^5}{258*60 + 3}}$$

$$\gamma = 0.398$$

Note: lead-lag motion causes negligible damage at this location.

A plot of life limiting strain for the 6 and 12 o'clock position of each layer is given in Figure 17.

The following is a sample calculation of the life limiting strain for the 6 or 12 o'clock position on the O.D. of the fourth layer:

The vibratory strain vectors due to flap ($\pm\ \Theta_x$), inplane load ($\pm\ V_c$) and vibratory out-of-plane load ($\pm\ V_n$) are all in the same direction and phase. The strain magnitudes are, therefore, directly additive.

$$\gamma_{v_1} = 3.58*0.0761 + 1.652*\left(\frac{315}{68000}\right) + 0.0709$$

$$\gamma_{v1} = 0.351$$

Note: Pitch change strain did not enter the above calculation because it is 90^o out of phase in both geometry and time but, its Miner's Rule effect will be considered in the following vector:

$$\gamma_{v_2} = 0.05077*6.54*0.107 = 0.0355$$

The life limiting strain is

$$\gamma = \sqrt[5]{\frac{258*60\ \left[\gamma^5_{v_1} + \gamma^5_{v_2}\right] + \left(\frac{\gamma cf}{2}\ \frac{*82000}{68000}\right)^5 + 2*\ \left(\frac{\gamma cf}{2}\right)^5}{258*60 + 1 + 2}}$$

$$\gamma = \sqrt[5]{\frac{258*60\ (.351^5 + .0355^5) + \left(\frac{1.652}{2}*\frac{82000}{68000}\right)^5 + 2*\ \left(\frac{1.652}{2}\right)^5}{258*60 + 3}}$$

$$\gamma = 0.352$$

Note: Lead-lag motion causes negligible damage at this location.

This life limiting strain is plotted for all layers in Figure 18.

The following is a sample calculation of the life limiting strain for the 3 and 9 o'clock position on the I.D. of the fourth layer:

The strain due to blade flapping is

$$\gamma_f = 3.58*0.0581 = 0.207$$

The strain due to vibitory C.F. is

$$\gamma_{cf} = \left(\frac{2.984}{2}\right) * \left(\frac{315}{68000}\right) = 0.0069$$

The strain due to lead-lag motion is

$$\gamma_{11} = 1.5*0.0803 = 0.120$$

The strain due to pitch change is

$$\gamma_{pc} = 0.0385*6.54*0.107 = 0.0269$$

These strains can be combined as shown in the following table;

STRAIN	TIME PHASE	DIRECTION	MAGNITUDE
γ_{pc}	0^{o}	0^{o}	0.0269
γ_{11}	0^{o}	90^{o}	0.120
In-phase resultant*	0^{o}	90^{o}	0.123
γ_{f}	90^{o}	90^{o}	0.207
γ_{cf}	90^{o}	90^{o}	0.0069
Out-of-phase resultant*	90^{o}	90^{o}	0.214

* Conventional vector combination

The resulting effective strain is

$$\gamma = \sqrt{(0.214)^2 + (0.123)^2} = 0.247$$

Note: in the general case of non-perpendicular phase resultants obtaining this effective strain vector is more complicated.

The life limiting strain is

$$\gamma = \sqrt[5]{\frac{258*60(0.247^5) + \left(\frac{2.984}{2}\frac{*82000}{68000}\right)^5 + 2*\left(\frac{2.984}{2}\right)^5}{258*60 + 3}}$$

$\gamma = .315$

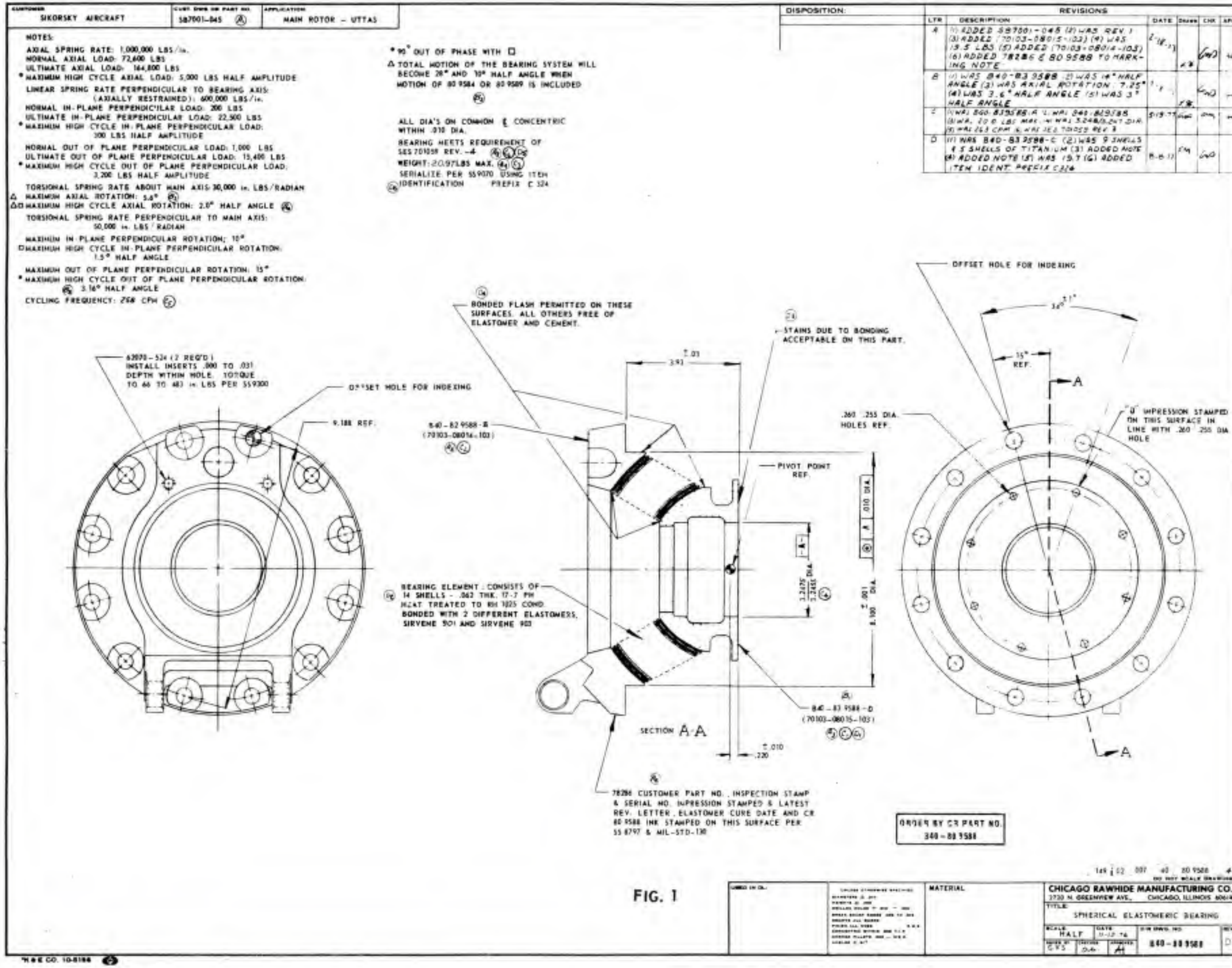
A plot of the life limiting strain for this location on all the shells is given in Figure 19. A plot for the O.D. is given in Figure 20.

On the basis of this analysis, first damage is predicted at

$$\text{LIFE} = \left(\frac{10.6}{0.398}\right)^{5} \Big/ \; 60*258$$

$$= 866 \text{ HR.}$$

The predicted location for first damage is the I.D. of the fourth layer. This location for first damage agrees with previous test results.


CUSTOMER
SIKORSKY AIRCRAFT
CUST DWG OR PART NO.
587001-045 (A)
APPLICATION
MAIN ROTOR - UTTAS
NOTES:
AXIAL SPRING RATE: 1,000,000 LBS/in.
NORMAL AXIAL LOAD: 72,600 LBS
ULTIMATE AXIAL LOAD: 144,800 LBS
* MAXIMUM HIGH CYCLE AXIAL LOAD: 5,000 LBS HALF AMPLITUDE
LINEAR SPRING RATE PERPENDICULAR TO BEARING AXIS: (AXIALLY RESTRAINED): 600,000 LBS/in.
NORMAL IN-PLANE PERPENDICULAR LOAD: 200 LBS
ULTIMATE IN-PLANE PERPENDICULAR LOAD: 22,500 LBS
* MAXIMUM HIGH CYCLE IN-PLANE PERPENDICULAR LOAD: 300 LBS HALF AMPLITUDE
NORMAL OUT OF PLANE PERPENDICULAR LOAD: 1,000 LBS
ULTIMATE OUT OF PLANE PERPENDICULAR LOAD: 15,400 LBS
* MAXIMUM HIGH CYCLE OUT OF PLANE PERPENDICULAR LOAD: 3,200 LBS HALF AMPLITUDE
TORSIONAL SPRING RATE ABOUT MAIN AXIS: 30,000 in. LBS/RADIAN
△ MAXIMUM AXIAL ROTATION: 5.8° (B)
△□ MAXIMUM HIGH CYCLE AXIAL ROTATION: 2.0° HALF ANGLE (B)
TORSIONAL SPRING RATE PERPENDICULAR TO MAIN AXIS: 50,000 in. LBS/RADIAN
MAXIMUM IN-PLANE PERPENDICULAR ROTATION: 10°
□ MAXIMUM HIGH CYCLE IN-PLANE PERPENDICULAR ROTATION: 1.5° HALF ANGLE
MAXIMUM OUT OF PLANE PERPENDICULAR ROTATION: 15°
* MAXIMUM HIGH CYCLE OUT OF PLANE PERPENDICULAR ROTATION: (B) 3.16° HALF ANGLE
CYCLING FREQUENCY: 268 CPM (C)
* 90° OUT OF PHASE WITH □
△ TOTAL MOTION OF THE BEARING SYSTEM WILL BECOME 28° AND 10° HALF ANGLE WHEN MOTION OF 80 9584 OR 80 9589 IS INCLUDED
ALL DIA'S ON COMMON ℄ CONCENTRIC WITHIN .010 DIA.
BEARING MEETS REQUIREMENT OF SES 701059 REV. -4
WEIGHT: 20.97 LBS MAX.
SERIALIZE PER SS9070 USING ITEM IDENTIFICATION PREFIX C 324
DISPOSITION:
REVISIONS
LTR | DESCRIPTION | DATE | DRAWN | CHK | APPR
A | (1) ADDED SS7001-045 (2) WAS REV. 1 (3) ADDED (70103-08015-103) (4) WAS 19.5 LBS (5) ADDED (70103-08014-103) (6) ADDED 78286 & 80 9588 TO MARKING NOTE
B | (1) WAS 840-83 9588 (2) WAS 14° HALF ANGLE (3) WAS AXIAL ROTATION 7.25° (4) WAS 3.6° HALF ANGLE (5) WAS 3° HALF ANGLE
C | 5-19-77
D | (1) WAS 840-83 9588-C (2) WAS 9 SHELLS & 5 SHELLS OF TITANIUM (3) ADDED NOTE (4) ADDED NOTE (5) WAS 19.7 (6) ADDED ITEM IDENT. PREFIX C324 | 8-6-77
63070-524 (2 REQ'D) INSTALL INSERTS .000 TO .031 DEPTH WITHIN HOLE. TORQUE TO 66 TO 483 in. LBS PER SS9300
OFFSET HOLE FOR INDEXING
9.188 REF.
BONDED FLASH PERMITTED ON THESE SURFACES. ALL OTHERS FREE OF ELASTOMER AND CEMENT.
840-82 9588-B (70103-08014-103)
STAINS DUE TO BONDING ACCEPTABLE ON THIS PART.
3.93 ±.03
PIVOT POINT REF.
.010 DIA.
3.2475 3.2455 DIA.
8.100 ±.001 DIA.
BEARING ELEMENT: CONSISTS OF 14 SHELLS - .062 THK. 17-7 PH HEAT TREATED TO RH 1025 COND. BONDED WITH 2 DIFFERENT ELASTOMERS, SIRVENE 901 AND SIRVENE 903
840-83 9588-D (70103-08015-103)
SECTION A-A
.220 ±.010
78286 CUSTOMER PART NO., INSPECTION STAMP & SERIAL NO. IMPRESSION STAMPED & LATEST REV. LETTER, ELASTOMER CURE DATE AND CR 80 9588 INK STAMPED ON THIS SURFACE PER SS 8797 & MIL-STD-130
OFFSET HOLE FOR INDEXING
15° REF.
.260 .255 DIA. HOLES REF.
"0" IMPRESSION STAMPED ON THIS SURFACE IN LINE WITH .260 .255 DIA HOLE
A
A
ORDER BY CR PART NO. 840-80 9588
MATERIAL
CHICAGO RAWHIDE MANUFACTURING CO.
2720 N. GREENVIEW AVE., CHICAGO, ILLINOIS 60614
TITLE
SPHERICAL ELASTOMERIC BEARING
SCALE HALF
840-80 9588
REV D
FIG. 1

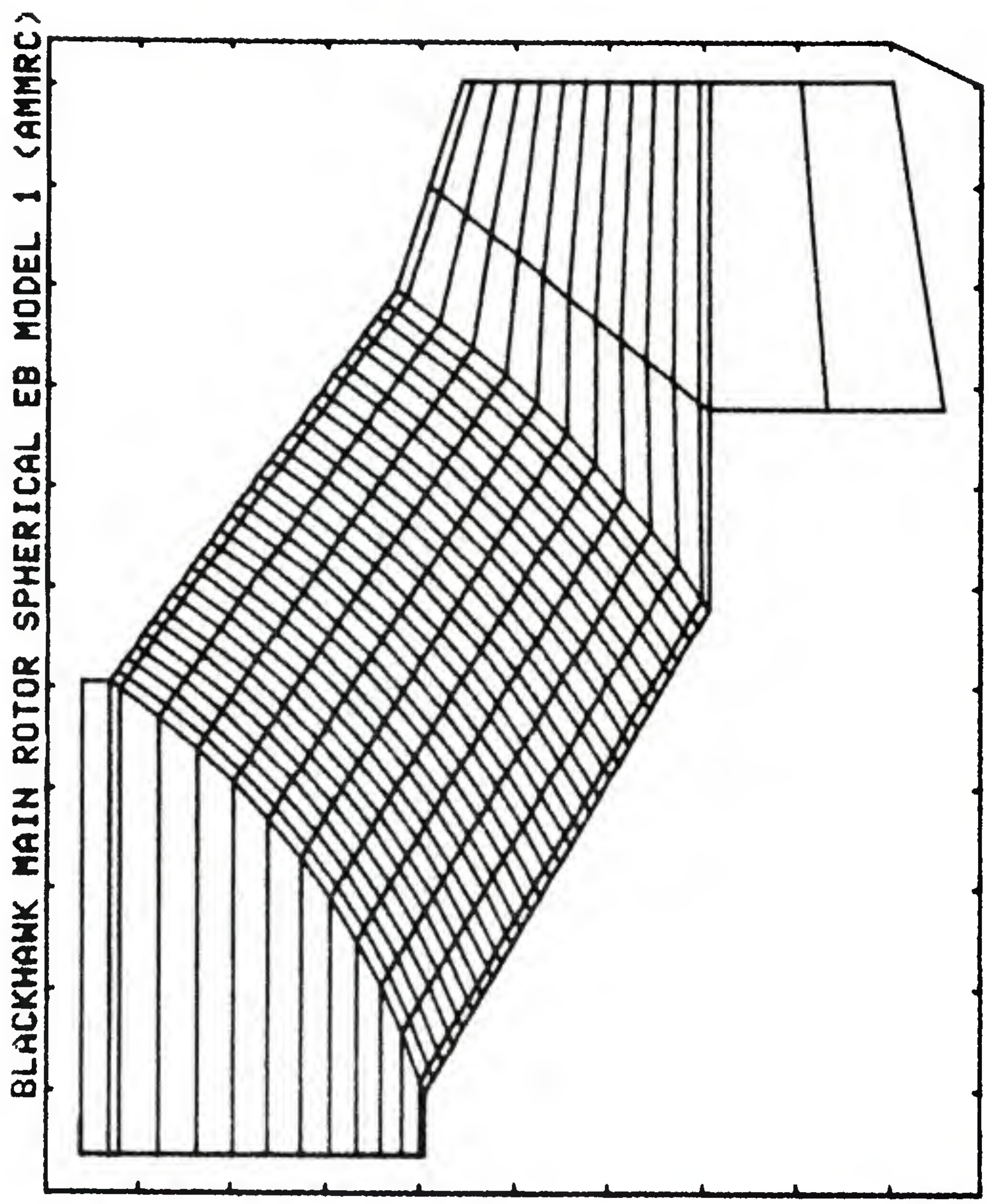
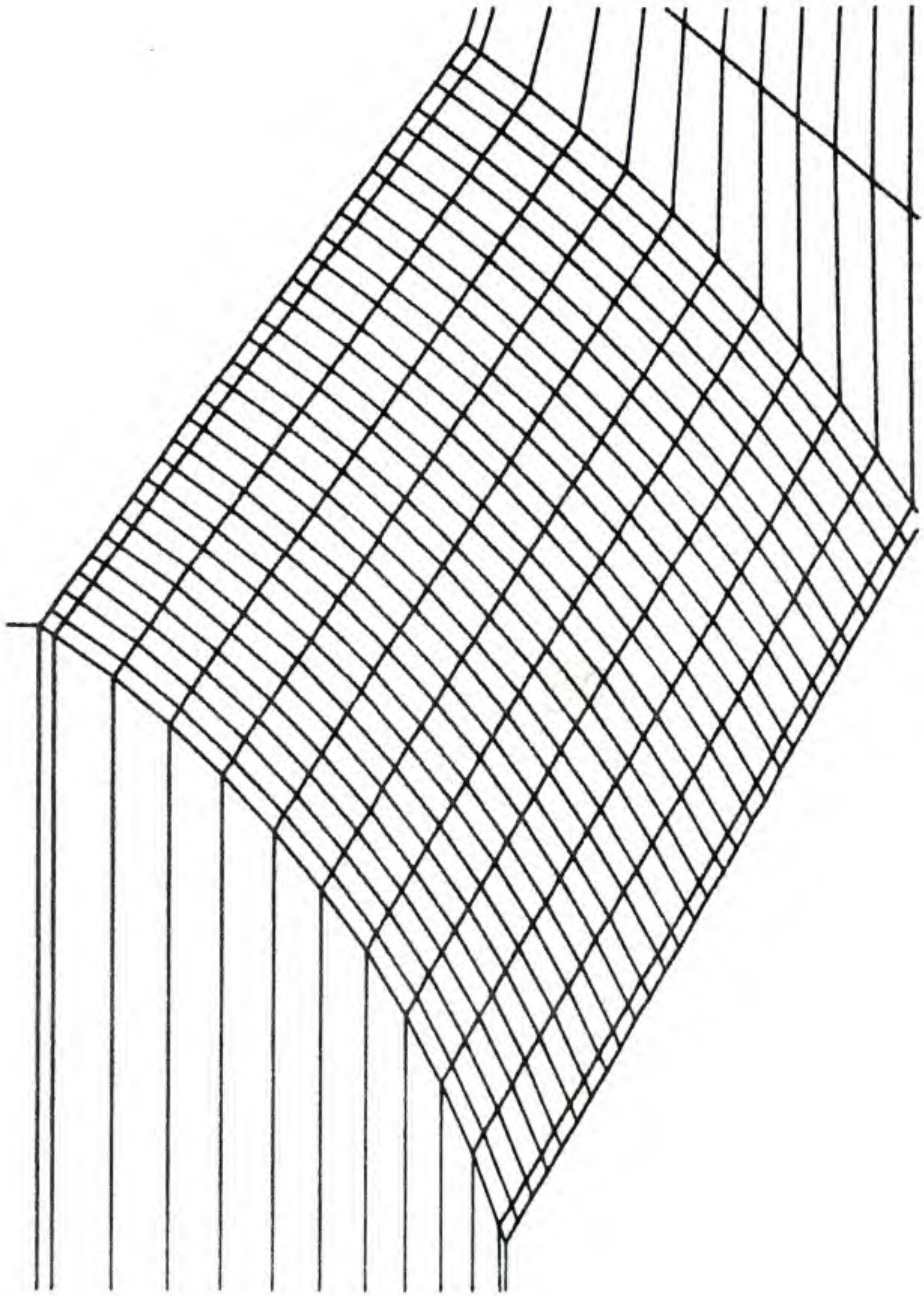
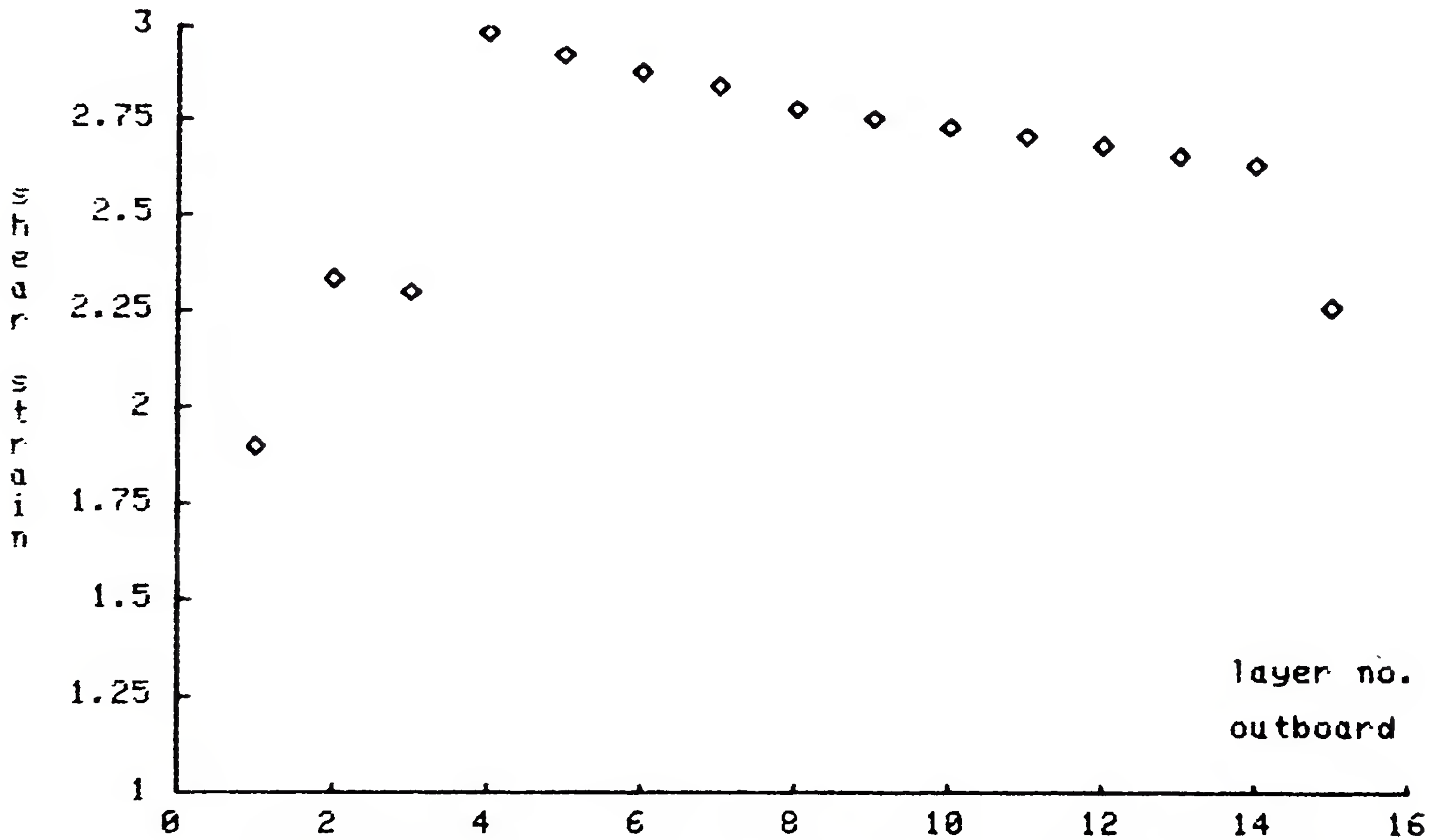


FIG. 2



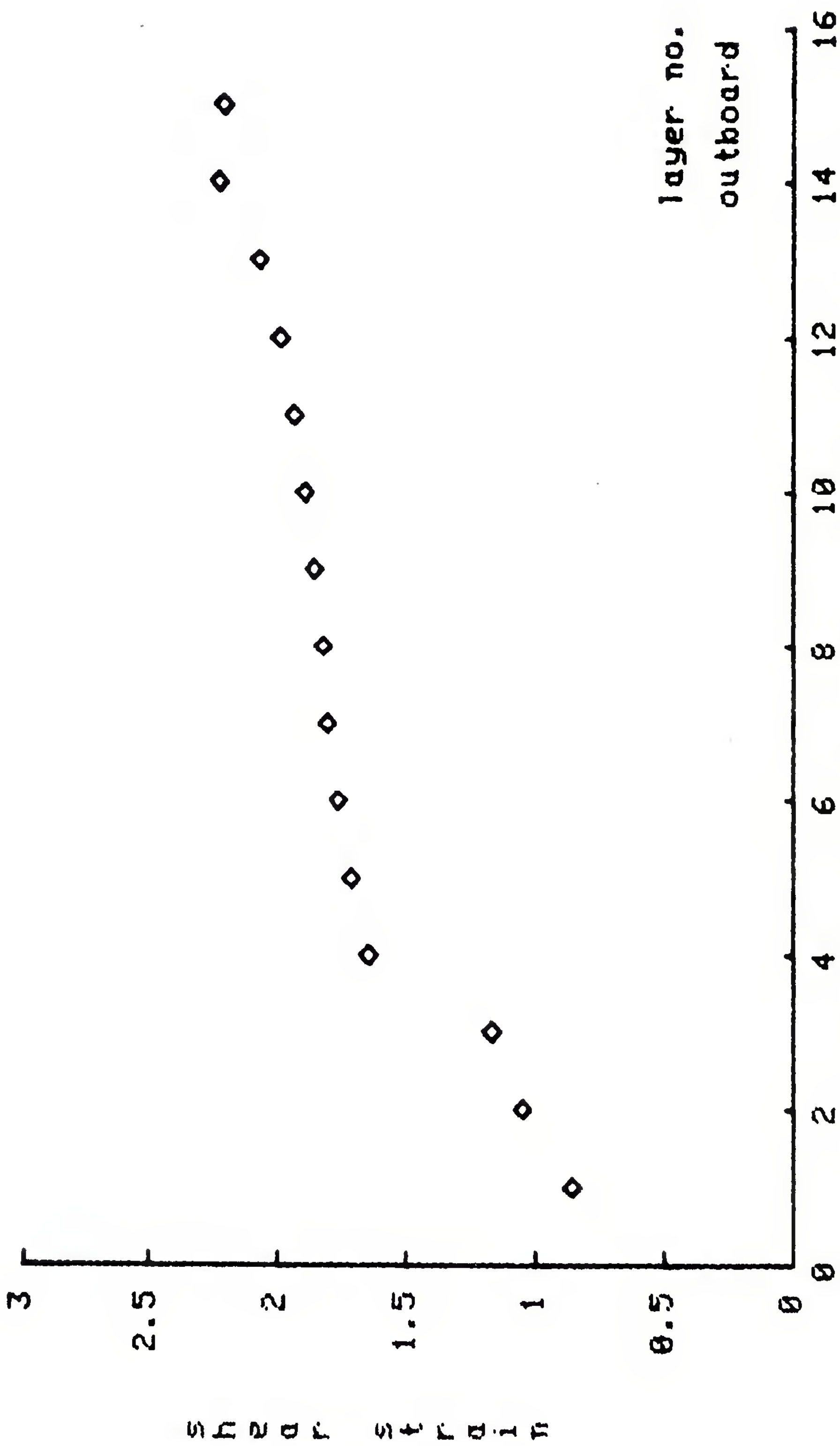
BLOW UP OF FIG. 2

FIG. 3



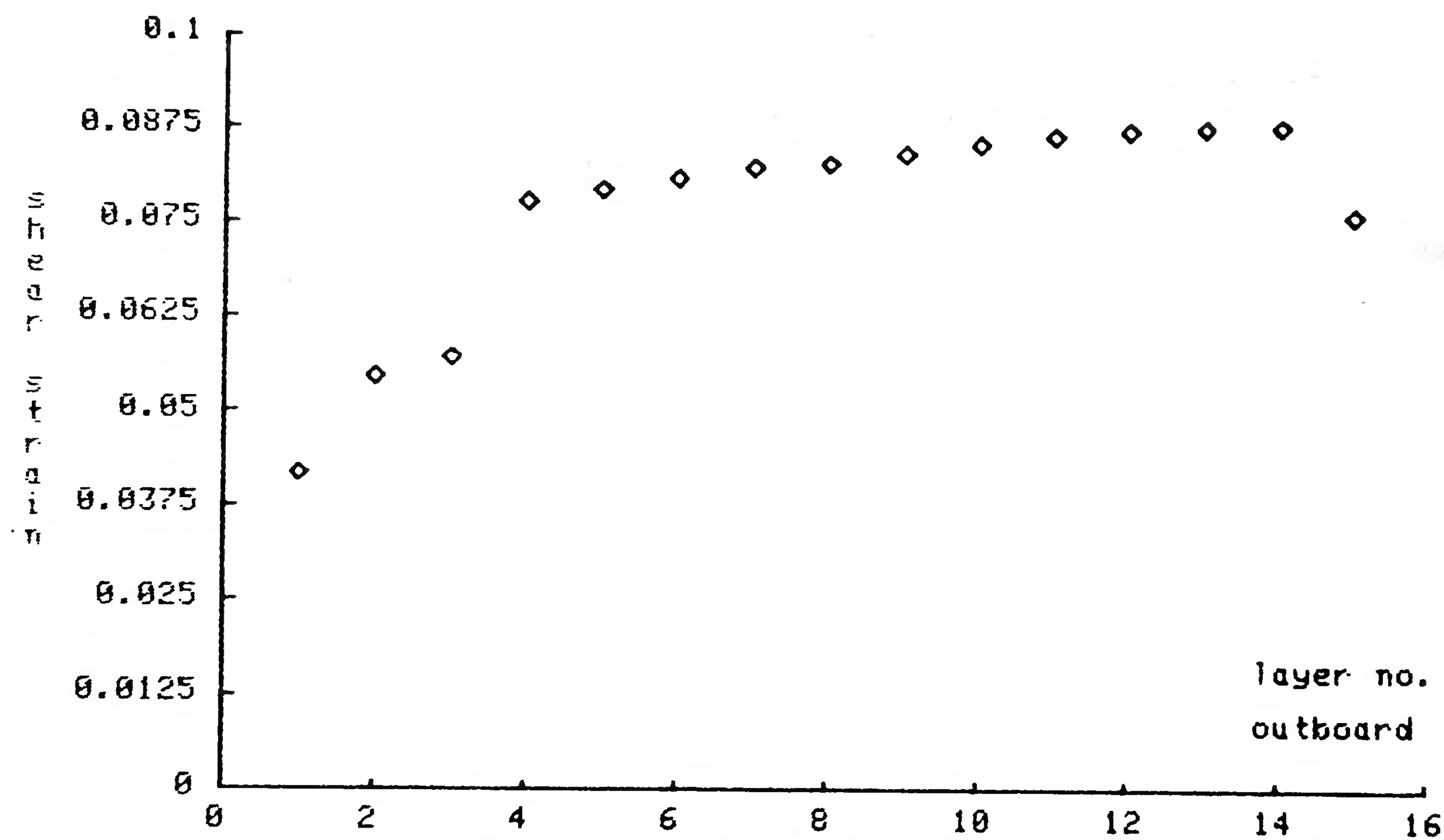
STRAIN ALONG I.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
@ 68,000 LBS. AXIAL LOAD
3/6/79

FIG. 4



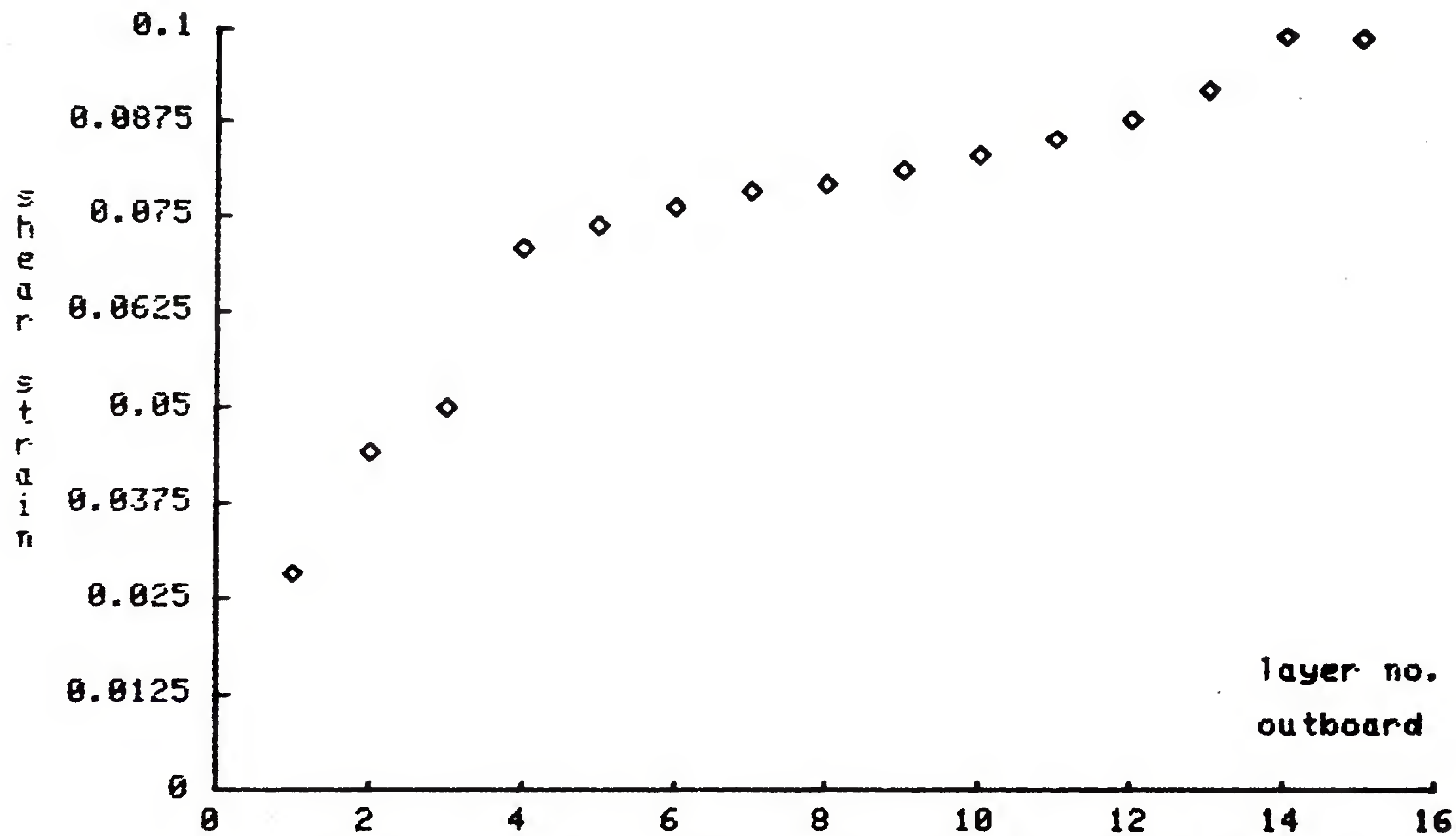
STRAIN ALONG O.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
@ 68000 LBS. AXIAL LOAD
3/6/79

FIG.5



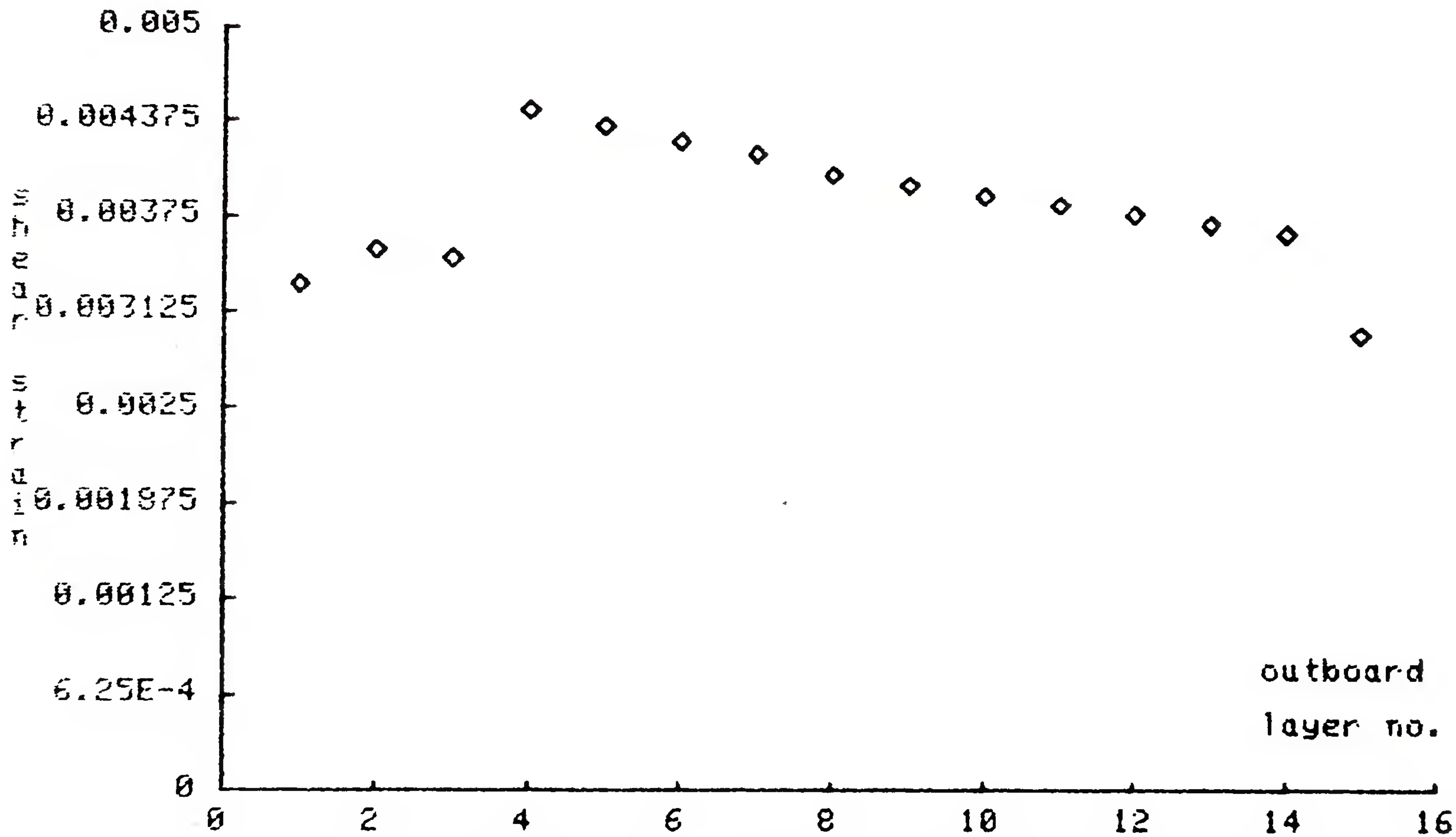
STRAIN ALONG I.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
@ 1292 LBS. LATERAL LOAD. 6 & 12 O'CLOCK POSITIONS.
3/9/79

FIG. 6



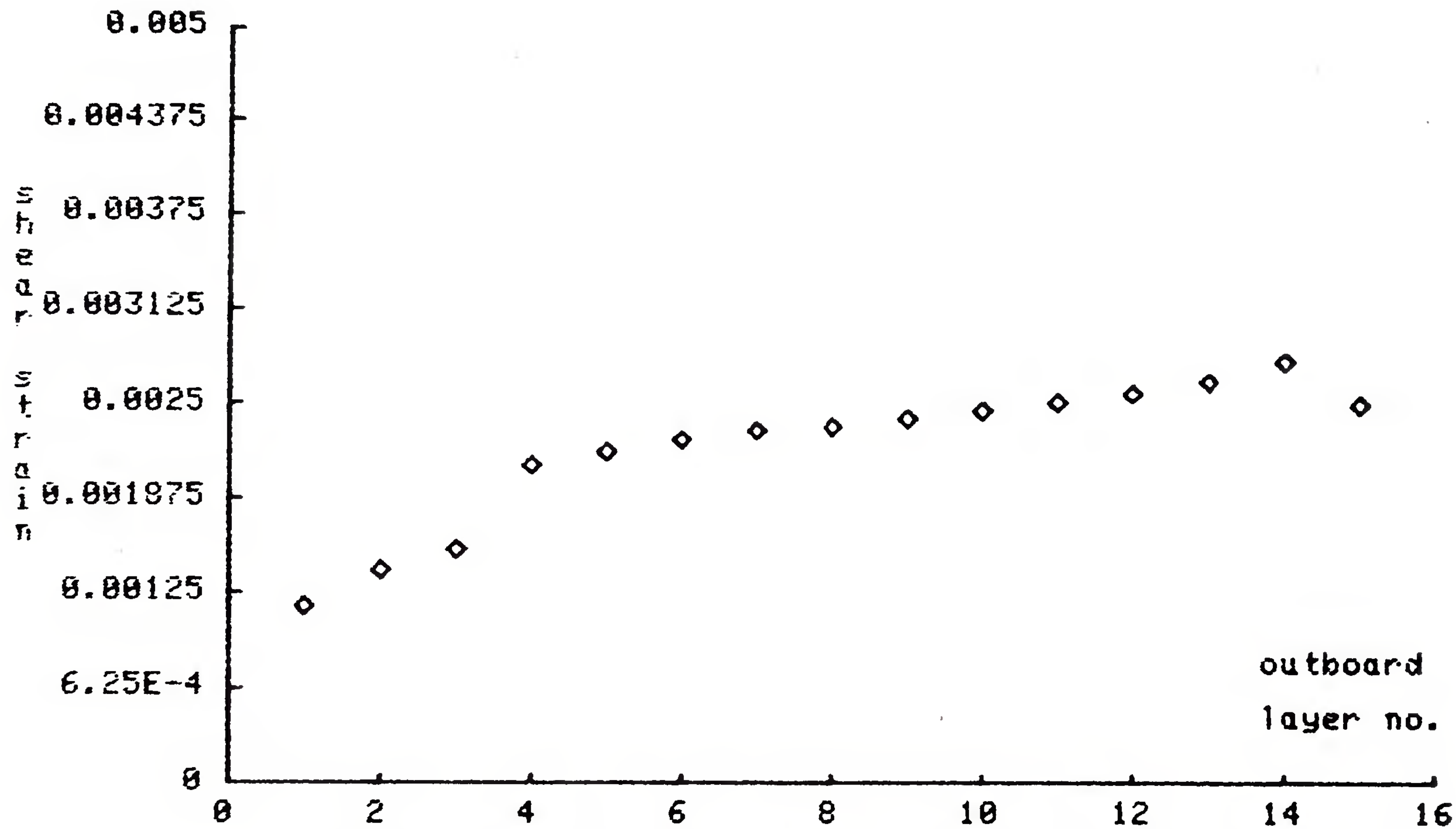
STRAIN ALONG O.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
@ 1292 LBS. LATERAL LOAD. 6 & 12 O'CLOCK POSITIONS.
3/9/79

FIG. 7



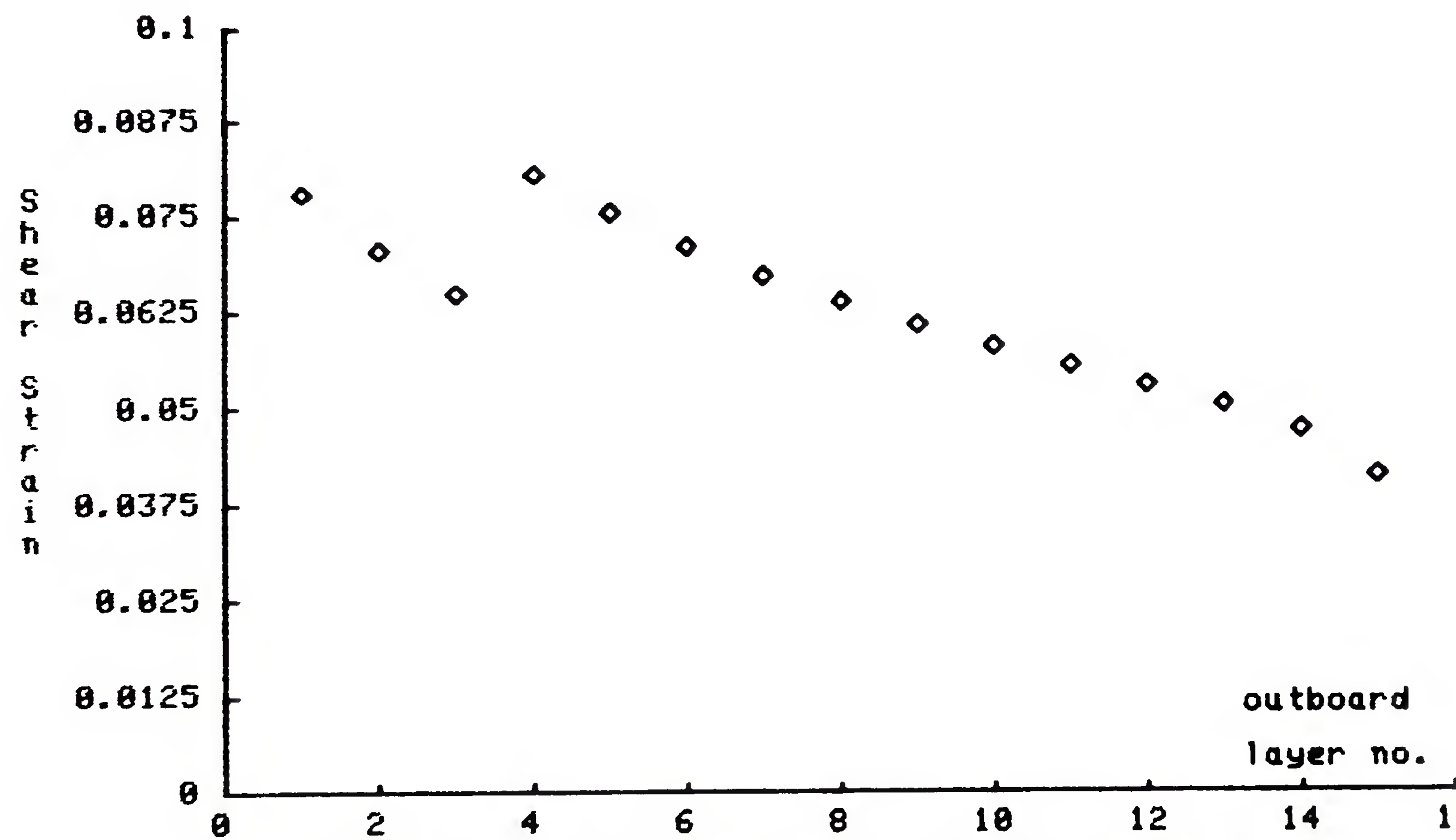
STRAIN ALONG I.D FOR AMMRC SPHERICAL EB (14 SHELLS)
@1292 LBS. LATERAL LOAD. 3 & 9 O'CLOCK POSITIONS.
3/16/79

FIG. 8



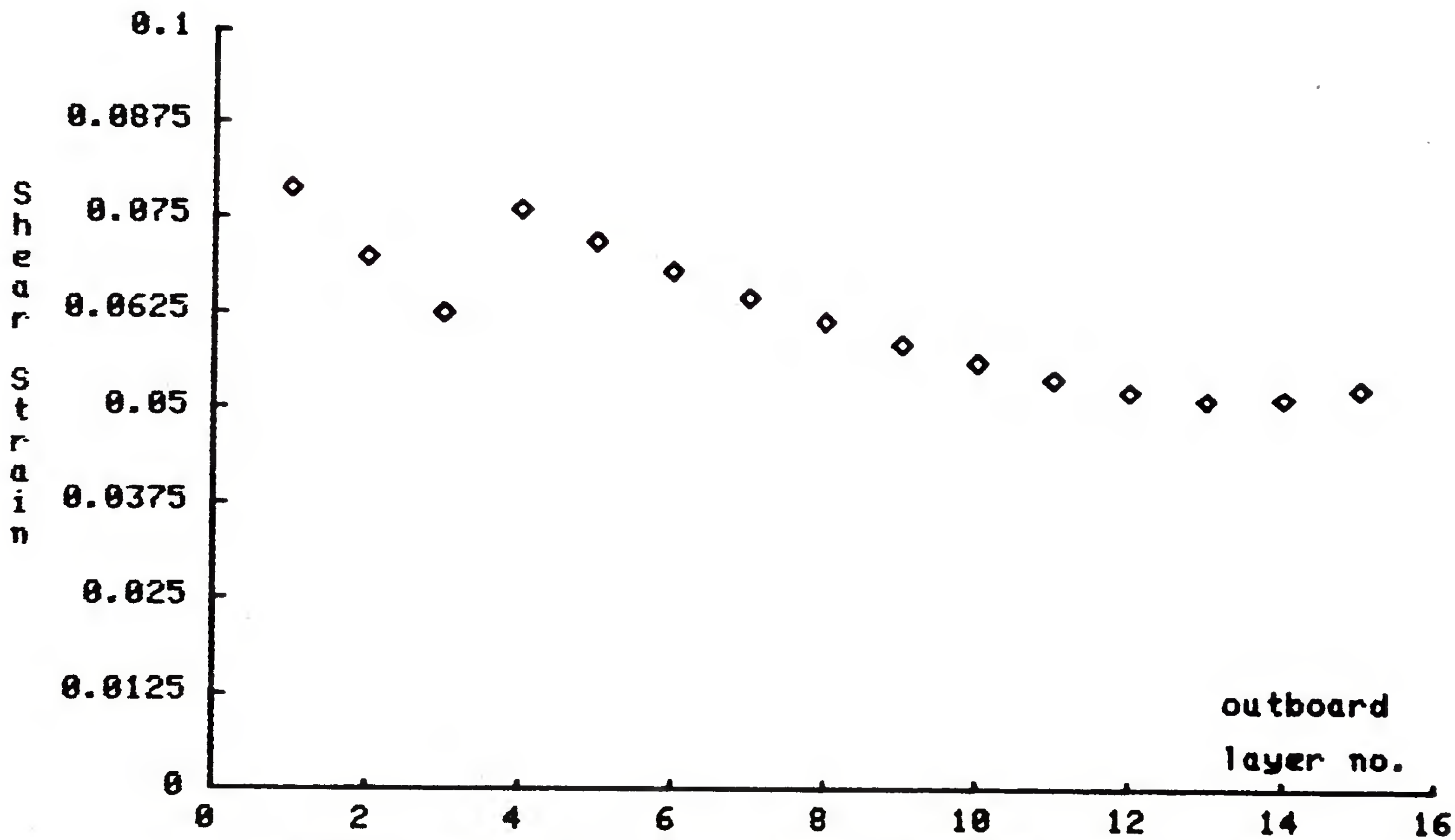
STRAIN ALONG O.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
@ 1292 LBS. LATERAL LOAD. 3 & 9 O'CLOCK POSITIONS.
3/16/79

FIG. 9



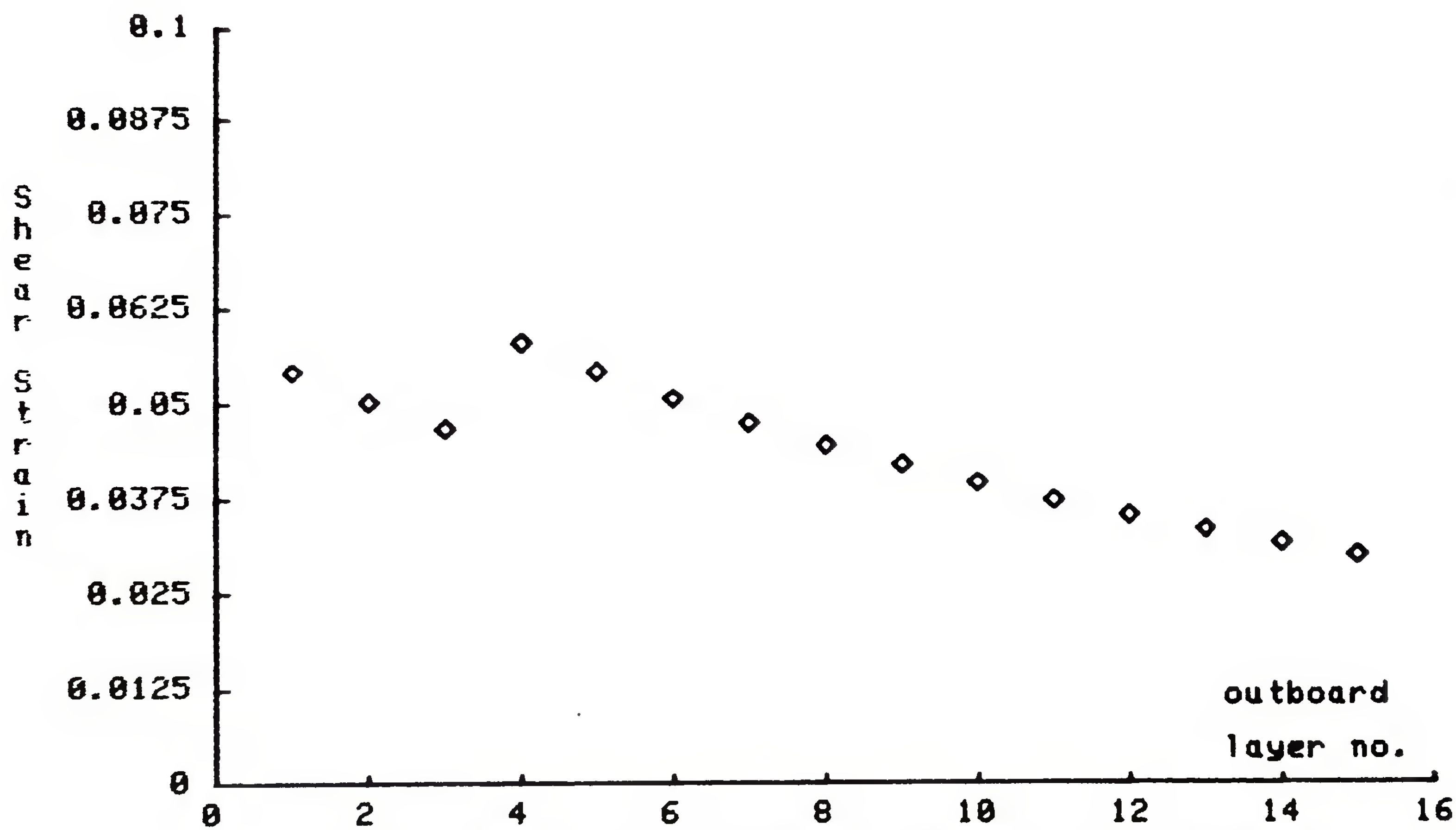
STRAIN ALONG I.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
COCKED 1 DEGREE. 6 & 12 O'CLOCK POSITIONS.
8/17/79

FIG. 10



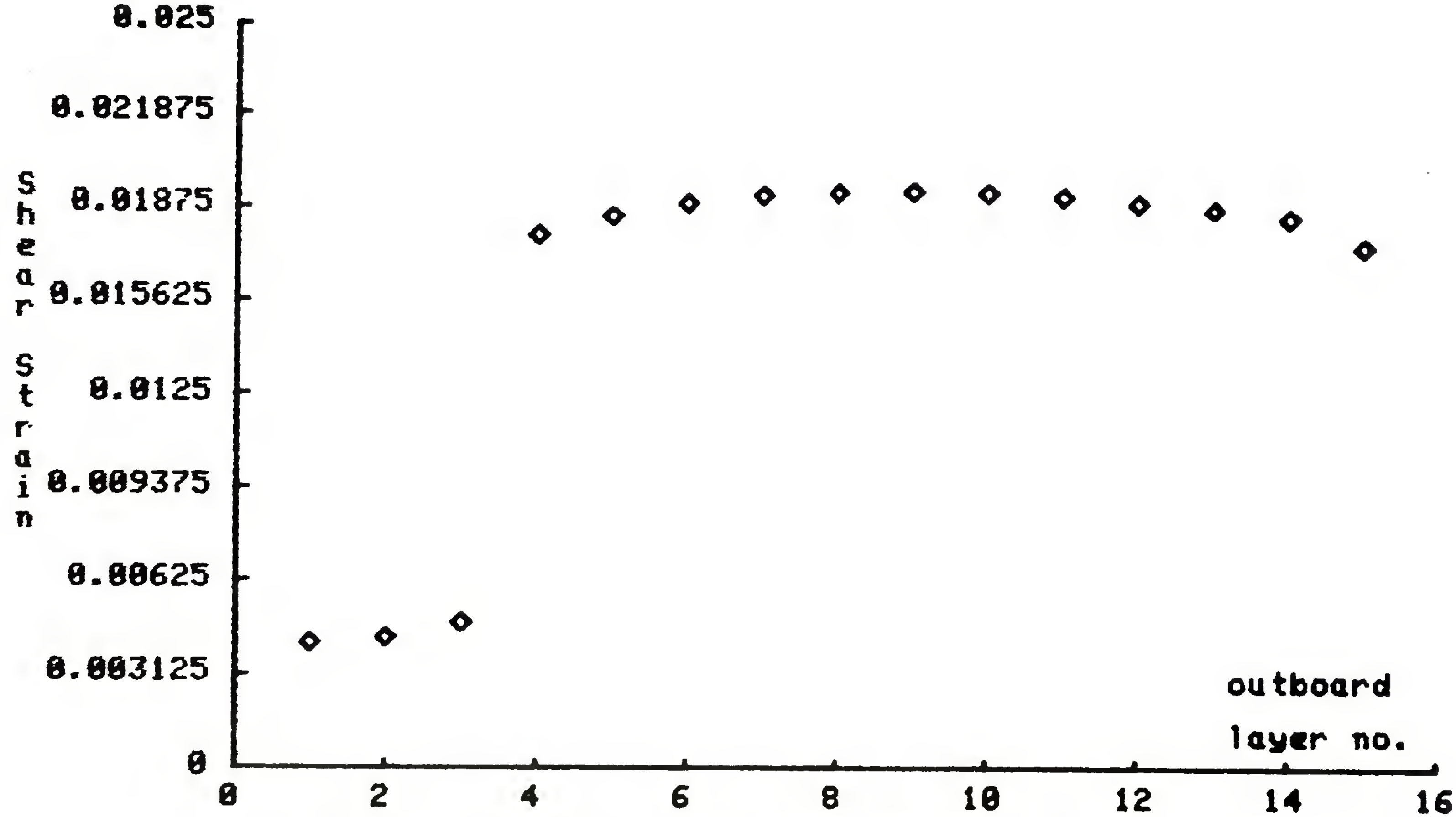
STRAIN ALONG O.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
COCKED 1 DEGREE. 6 & 12 O'CLOCK POSITIONS.
8/17/79

FIG. 11



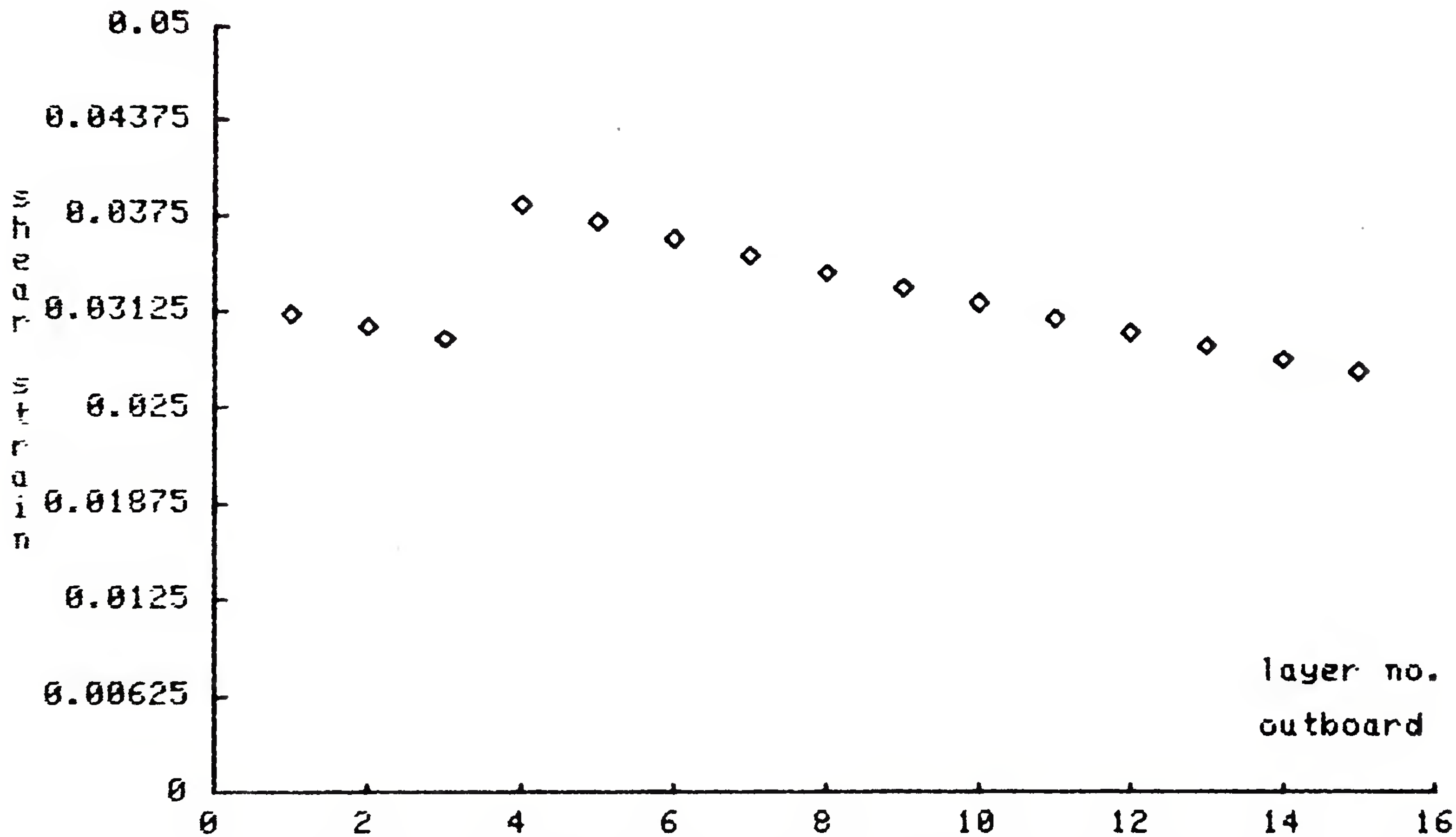
STRAIN ALONG I.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
COCKED 1 DEGREE. 3 & 9 O'CLOCK POSITIONS.
8/17/79

FIG. 12



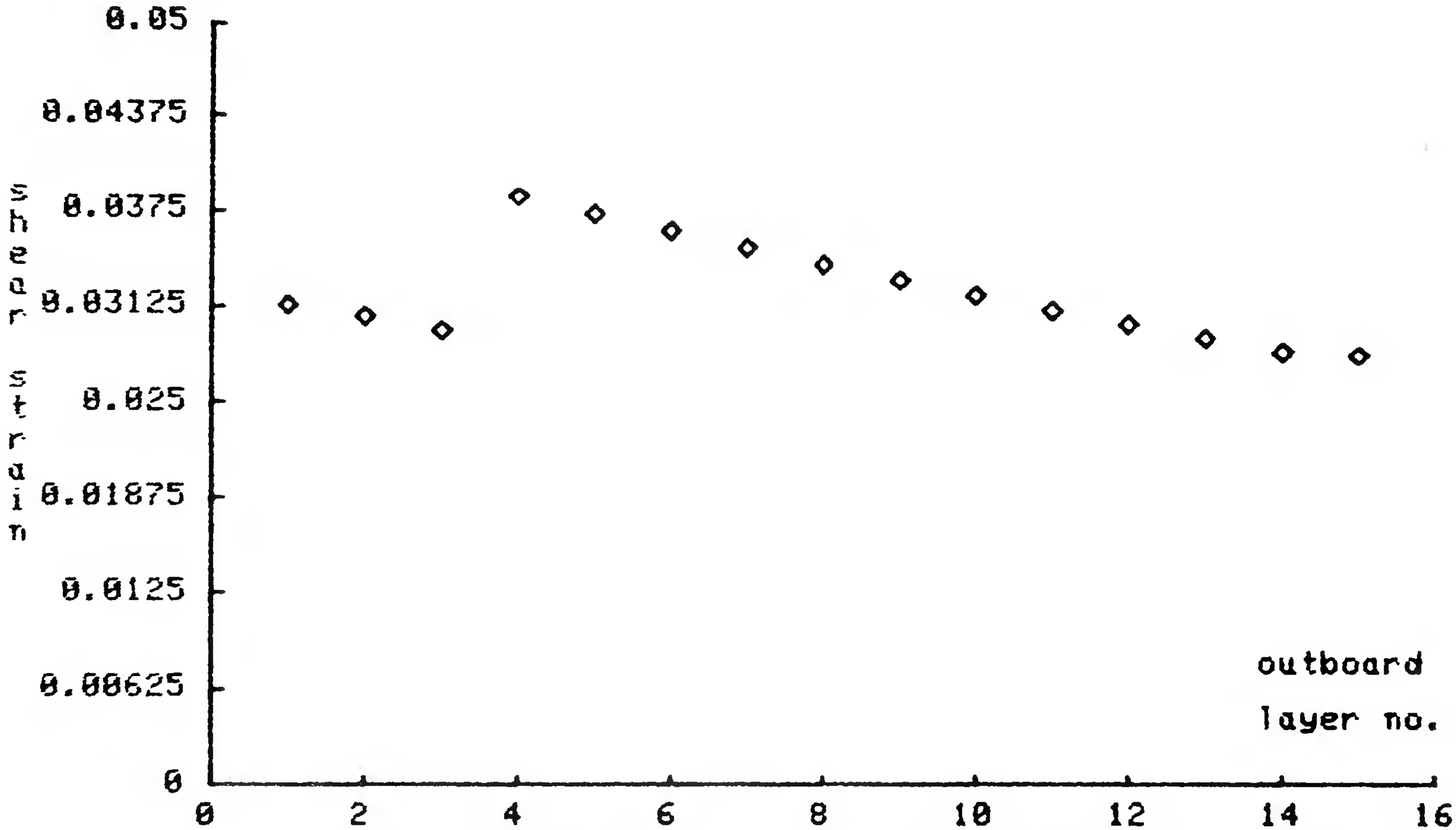
STRAIN ALONG O.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
COCKED 1 DEGREE. 3 & 9 O'CLOCK POSITIONS.
8/17/79

FIG. 13



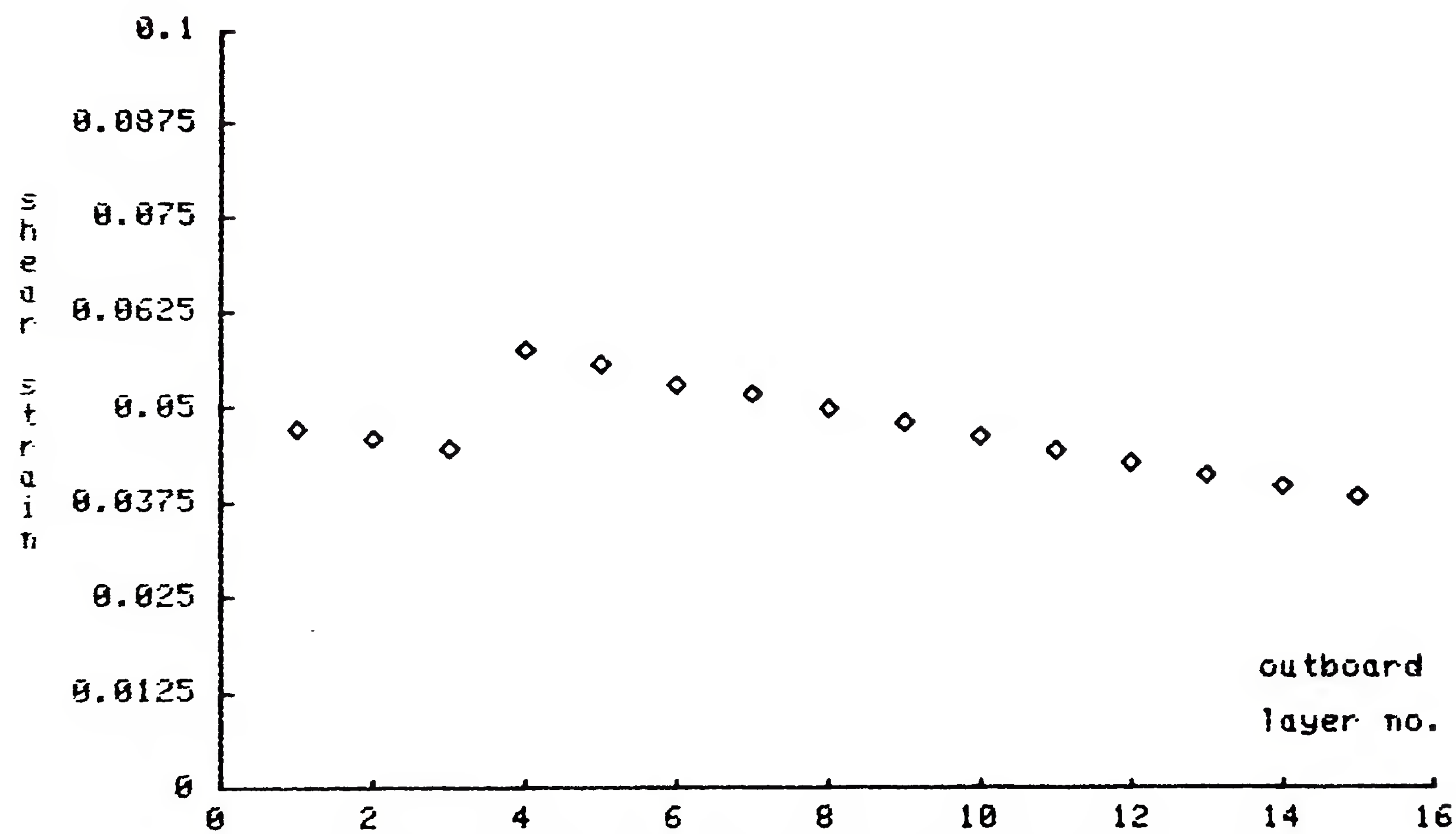
1 DEGREE PITCH CHANGE STRAIN (THEORETICAL) ALONG I.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
2/28/79

FIG. 14



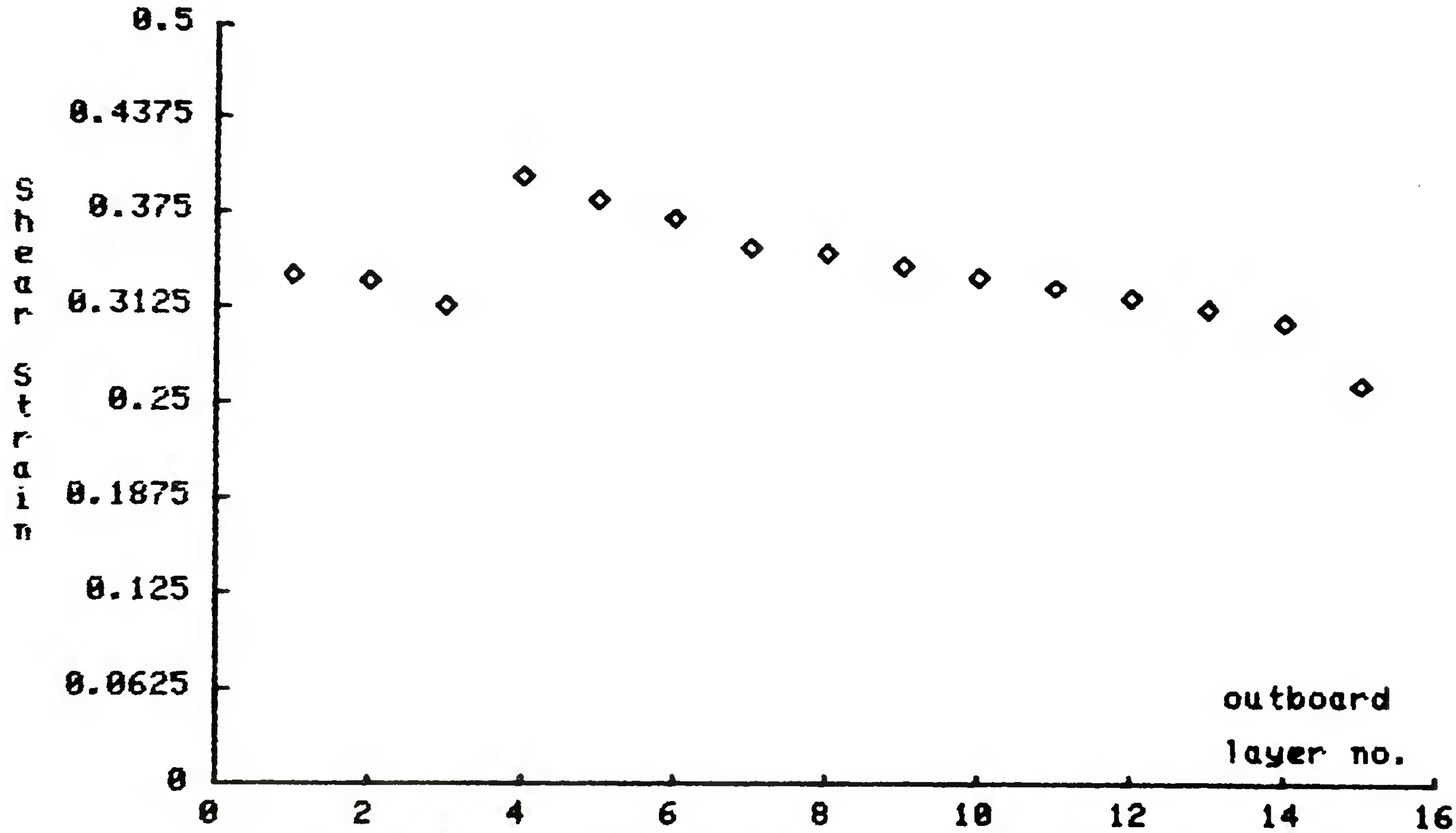
1 DEGREE PITCH CHANGE STRAIN (F.E.) ALONG I.D. FOR
AMMRC SPHERICAL EB (14 SHELLS)
3/14/79

FIG. 15



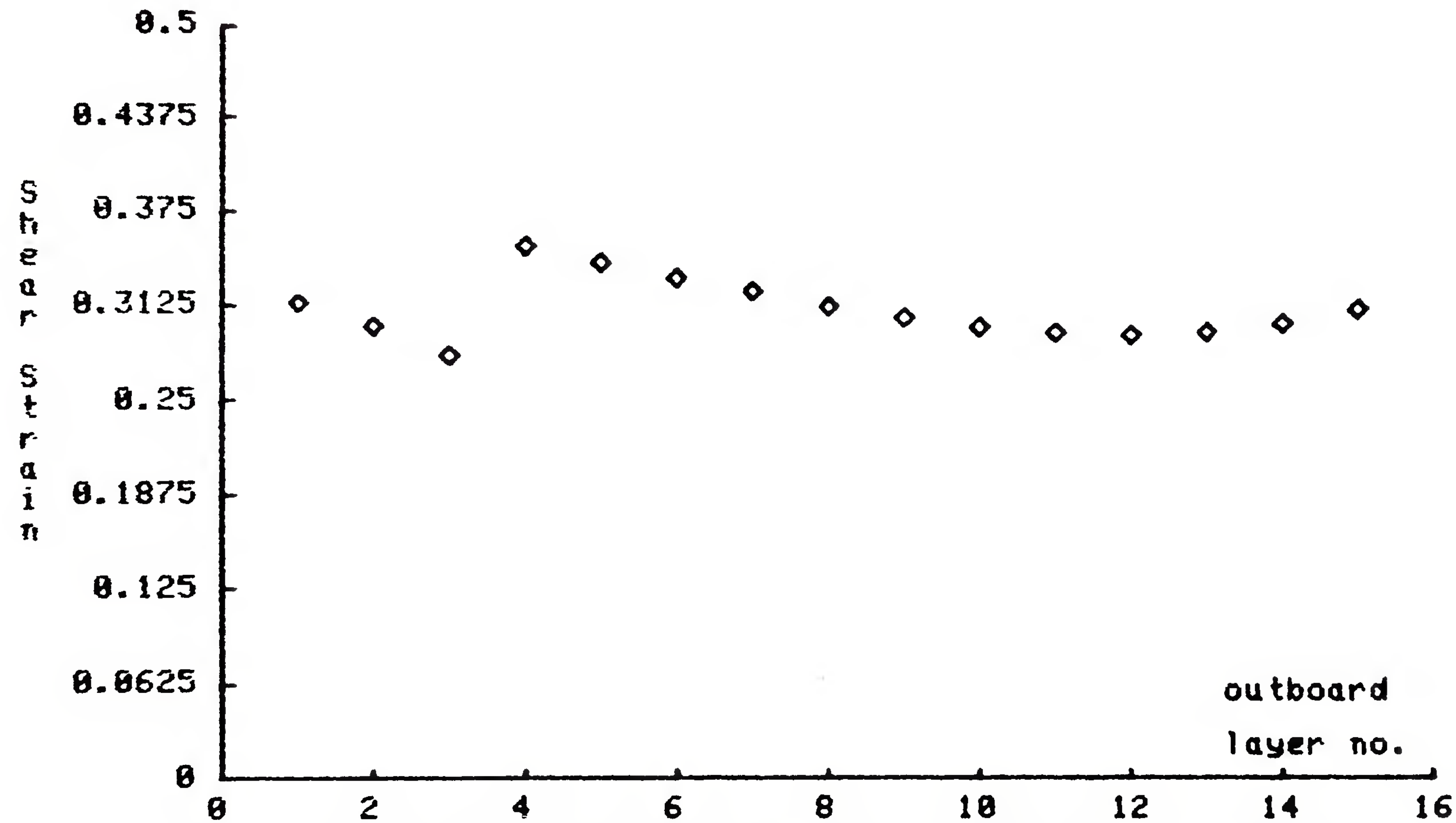
1 DEGREE PITCH CHANGE STRAIN (F.E.) ALONG O.D. FOR
AMMRC SPHERICAL EB (14) SHELLS
3/16/79

FIG.16



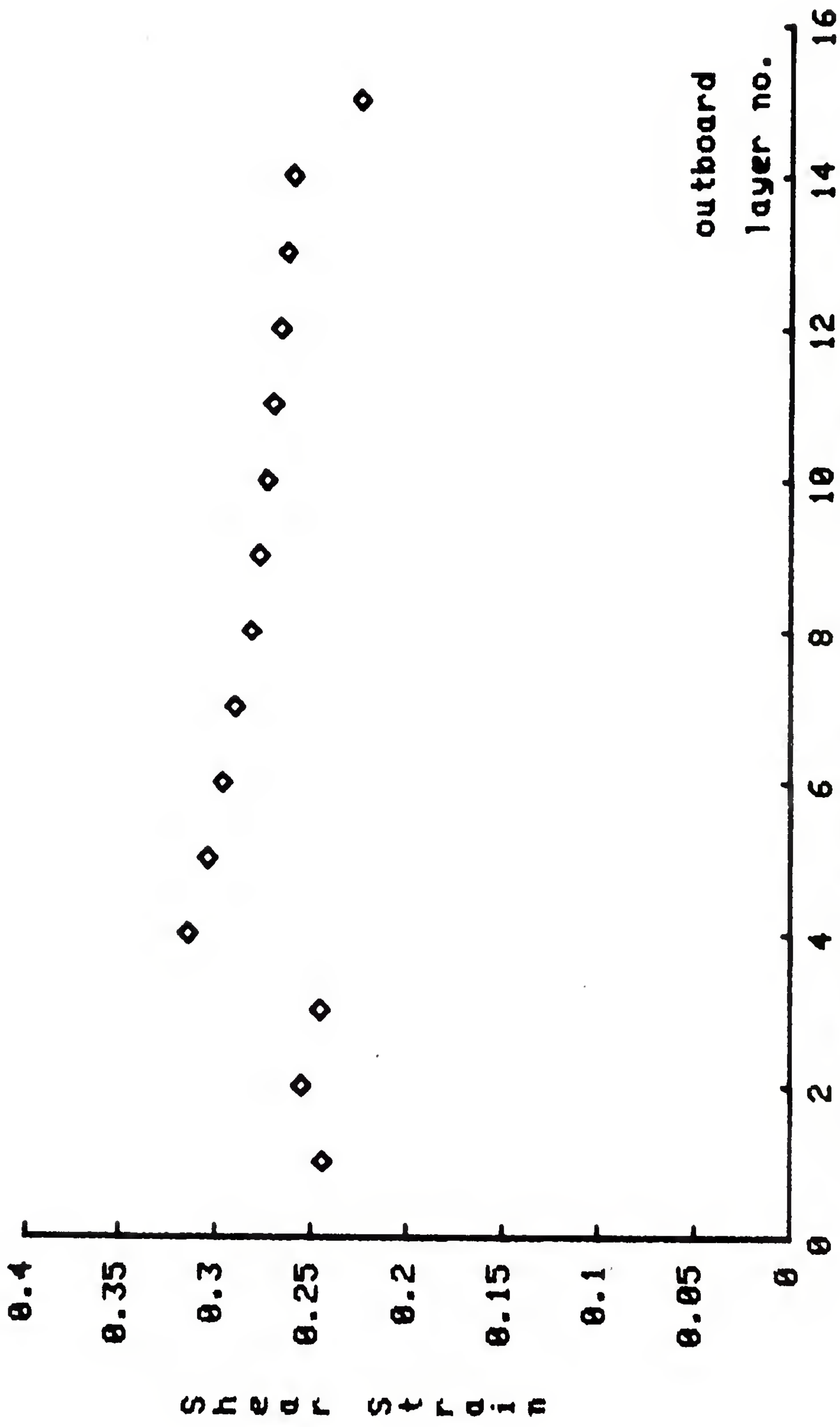
LIFE LIMITING STRAIN ALONG I.D. FOR AMMRC SPHERICAL
EB (14 SHELLS). 6 & 12 O'CLOCK POSITIONS.
8/17/79

FIG. 17



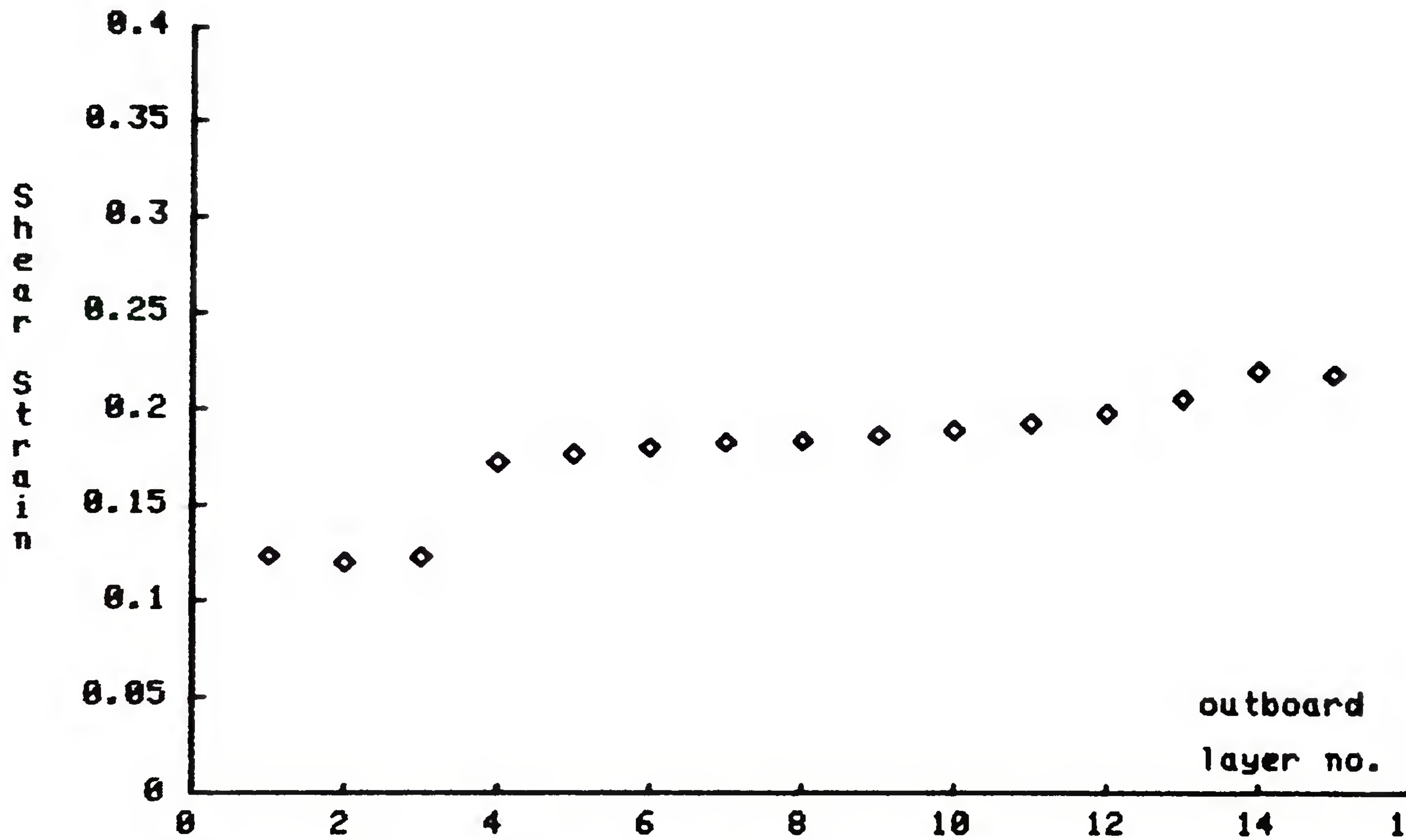
LIFE LIMITING STRAIN ALONG O.D. FOR AMMRC SPHERICAL
EB (14 SHELLS). 6 & 12 O'CLOCK POSITIONS.
8/17/79

FIG. 18



LIFE LIMITING STRAIN ALONG I.D. FOR AMMRC SPHERICAL EB (14 SHELLS). 3 & 9 O'CLOCK POSITIONS.
12/20/79

FIG. 19



LIFE LIMITING STRAIN ALONG O.D. FOR AMMRC SPHERICAL
EB (14 SHELLS). 3 & 9 O'CLOCK POSITIONS.
12/20/79

FIG. 20

A P P E N D I X   I

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1:$ BLACKHAWK MAIN ROTOR SPHERICAL EB MODEL 1 (AMMRC)
2:SETUP,4,PRESCRIB,18
3:RUBBER,1,600,.4995
4:RUBBER,2,450,.4996
5:ALUMNM,3,10E6,.33
6:SSTEEL,4,28E6,.3
7:TITANM,5,15E6,.3
8:END,MATERIAL
9:1,1,2,2
10:1.375,1.5,1.5,1.375
11:.744,.744,2.61,2.61
12:2,1,3,1
13:1.5,1.543,1.543,1.5
14:.744,.744,.744,.744
15:4,1,5,1
16:1.716,1.881,1.881,1.716
17:.744,.744,.744,.744
18:6,1,7,1
19:2.037,2.184,2.184,2.037
20:.744,.744,.744,.744
21:8,1,9,1
22:2.320,2.445,2.445,2.320
23:.744,.744,.744,.744
24:10,1,11,1
25:2.560,2.662,2.662,2.560
26:.744,.744,.744,.744
27:12,1,13,1
28:2.752,2.829,2.829,2.752
29:.744,.744,.744,.744
30:13,1,14,1
31:2.829,2.8455,2.8455,2.829
32:.744,.744,.744,.744
33: 2, 2, 3, 3,1,1,1,1,POLAR,0,0
34:3.010,3.010,3.062,3.062
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35:60.110,59.158,59.038,59.974
36: 3, 2,13, 3,1,1,1,1,POLAR,0,0
37:3.010,3.010,3.062,3.062
38:59.158,19.982,20.742,59.038
39:13, 2,14, 3,1,1,1,1,POLAR,0,0
40:3.010,3.010,3.062,3.062
41:19.982,19.030,19.812,20.742
42: 2, 4, 3, 5,1,1,1,1,POLAR,0,0
43:3.124,3.124,3.188,3.188
44:59.817,58.900,58.764,59.662
45: 3, 4,13, 5,1,1,1,1,POLAR,0,0
46:3.124,3.124,3.188,3.188
47:58.900,21.607,22.455,58.764
48:13, 4,14, 5,1,1,1,1,POLAR,0,0
49:3.124,3.124,3.188,3.188
50:21.607,20.700,21.570,22.455
51: 2, 6, 3, 7,1,1,1,1,POLAR,0,0
52:3.250,3.250,3.316,3.316
53:59.517,58.636,58.506,59.370
54: 3, 6,13, 7,1,1,1,1,POLAR,0,0
55:3.250,3.250,3.316,3.316
56:58.636,23.236,24.028,58.506
57:13, 6,14, 7,1,1,1,1,POLAR,0,0
58:3.250,3.250,3.316,3.316
59:23.236,22.371,23.184,24.028
60: 2, 8, 3, 9,1,1,1,1,POLAR,0,0
61:3.378,3.378,3.446,3.446
62:59.236,58.389,58.265,59.095
63: 3, 8,13, 9,1,1,1,1,POLAR,0,0
64:3.378,3.378,3.446,3.446
65:58.389,24.738,25.481,58.265
66:13, 8,14, 9,1,1,1,1,POLAR,0,0
67:3.378,3.378,3.446,3.446
68:24.738,23.911,24.672,25.481
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```
69: 2,10, 3,11,1,1,1,1,POLAR,0,0
70:3.508,3.508,3.578,3.578
71:58.972,58.156,58.037,58.837
72: 3,10,13,11,1,1,1,1,POLAR,0,0
73:3.508,3.508,3.578,3.578
74:58.156,26.128,26.826,58.037
75:13,10,14,11,1,1,1,1,POLAR,0,0
76:3.508,3.508,3.578,3.578
77:26.128,25.334,26.049,26.826
78: 2,12, 3,13,1,1,1,1,POLAR,0,0
79:3.640,3.640,3.712,3.712
80:58.723,57.936,57.823,58.594
81: 3,12,13,13,1,1,1,1,POLAR,0,0
82:3.640,3.640,3.712,3.712
83:57.936,27.418,28.076,57.823
84:13,12,14,13,1,1,1,1,POLAR,0,0
85:3.640,3.640,3.712,3.712
86:27.418,26.655,27.329,28.076
87: 2,14, 3,15,1,1,1,1,POLAR,0,0
88:3.774,3.774,3.848,3.848
89:58.488,57.729,57.621,58.365
90: 3,14,13,15,1,1,1,1,POLAR,0,0
91:3.774,3.774,3.848,3.848
92:57.729,28.620,29.242,57.621
93:13,14,14,15,1,1,1,1,POLAR,0,0
94:3.774,3.774,3.848,3.848
95:28.620,27.884,28.521,29.242
96: 2,16, 3,17,1,1,1,1,POLAR,0,0
97:3.910,3.910,3.985,3.985
98:58.266,57.534,57.432,58.150
99: 3,16,13,17,1,1,1,1,POLAR,0,0
100:3.910,3.910,3.985,3.985
101:57.534,29.743,30.324,57.432
102:13,16,14,17,1,1,1,1,POLAR,0,0
```

```
103:3.910,3.910,3.985,3.985
104:29.743,29.032,29.627,30.324
105: 2,18, 3,19,1,1,1,1,POLAR,0,0
106:4.047,4.047,4.124,4.124
107:58.058,57.350,57.253,57.947
108: 3,18,13,19,1,1,1,1,POLAR,0,0
109:4.047,4.047,4.124,4.124
110:57.350,30.787,31.339,57.253
111:13,18,14,19,1,1,1,1,POLAR,0,0
112:4.047,4.047,4.124,4.124
113:30.787,30.099,30.663,31.339
114: 2,20, 3,21,1,1,1,1,POLAR,0,0
115:4.186,4.186,4.265,4.265
116:57.860,57.176,57.083,57.754
117: 3,20,13,21,1,1,1,1,POLAR,0,0
118:4.186,4.186,4.265,4.265
119:57.176,31.767,32.292,57.083
120:13,20,14,21,1,1,1,1,POLAR,0,0
121:4.186,4.186,4.265,4.265
122:31.767,31.100,31.637,32.292
123: 2,22, 3,23,1,1,1,1,POLAR,0,0
124:4.327,4.327,4.408,4.408
125:57.673,57.011,56.921,57.571
126: 3,22,13,23,1,1,1,1,POLAR,0,0
127:4.327,4.327,4.408,4.408
128:57.011,32.689,33.190,56.921
129:13,22,14,23,1,1,1,1,POLAR,0,0
130:4.327,4.327,4.408,4.408
131:32.689,32.042,32.553,33.190
132: 2,24, 3,25,1,1,1,1,POLAR,0,0
133:4.470,4.470,4.553,4.553
134:57.495,56.855,56.768,57.397
135: 3,24,13,25,1,1,1,1,POLAR,0,0
136:4.470,4.470,4.553,4.553
```

```
137:56.855,33.559,34.036,56.768
138:13,24,14,25,1,1,1,1,POLAR,0,0
139:4.470,4.470,4.553,4.553
140:33.559,32.930,33.417,34.036
141: 2,26, 3,27,1,1,1,1,POLAR,0,0
142:4.615,4.615,4.700,4.700
143:57.326,56.706,56.623,57.232
144: 3,26,13,27,1,1,1,1,POLAR,0,0
145:4.615,4.615,4.700,4.700
146:56.706,34.380,34.836,56.623
147:13,26,14,27,1,1,1,1,POLAR,0,0
148:4.615,4.615,4.700,4.700
149:34.380,33.768,34.233,34.836
150: 2,28, 3,29,1,1,1,1,POLAR,0,0
151:4.762,4.762,4.849,4.849
152:57.166,56.564,56.484,57.075
153: 3,28,13,29,1,1,1,1,POLAR,0,0
154:4.762,4.762,4.849,4.849
155:56.564,35.157,35.592,56.484
156:13,28,14,29,1,1,1,1,POLAR,0,0
157:4.762,4.762,4.849,4.849
158:35.157,34.560,35.005,35.592
159: 2,30, 3,31,1,1,1,1,POLAR,0,0
160:4.911,4.911,4.985,4.985
161:57.013,56.429,56.365,56.940
162: 3,30,13,31,1,1,1,1,POLAR,0,0
163:4.911,4.911,4.985,4.985
164:56.429,35.892,36.240,56.365
165:13,30,14,31,1,1,1,1,POLAR,0,0
166:4.911,4.911,4.985,4.985
167:35.892,35.311,35.665,36.240
168:2,32,3,33
169:2.8597,2.9017,3.042,3
170:4.593,4.4659,5.008,5.008
```

```
171:3,32,13,33
172:2.9017,4.008,4.008,3.042
173:4.5659,3.7281,5.008,5.008
174:13,32,14,33
175:4.008,4.05,4.05,4.008
176:3.7281,3.701,5.008,5.008
177:14,32,16,33
178:4.05,5.065,4.835,4.05
179:3.701,3.701,5.008,5.008
180:END,GRID
181:ILOOP,13,1
182:QUAD,3,1,1
183:IEND
184:ILOOP,13,1
185:BC,PRESSURE,1,1,1,3487.63
186:IEND
187:JLOOP,3,2
188:ILOOP,12,1
189:QUAD,1,2,2
190:IEND
191:ILOOP,12,1
192:QUAD,4,2,3
193:IEND
194:JEND
195:JLOOP,11,2
196:ILOOP,12,1
197:QUAD,2,2,8
198:IEND
199:ILOOP,12,1
200:QUAD,4,2,9
201:IEND
202:JEND
203:ILOOP,12,1
204:QUAD,2,2,30
```

```
205:IEND
206:JLOOP,2,1
207:ILOOP,12,1
208:QUAD,5,2,31
209:IEND
210:JEND
211:QUAD,5,14,32
212:QUAD,5,15,32
213:ILOOP,2,1
214:BC,UR,14,32,1,0
215:BC,UZ,14,32,1,0
216:IEND
217:ILOOP,14,1
218:BC,UZ,2,32,3,0
219:IEND
220:PLOT,ELEMENTS,1.225,.594,5.215,5.128,10
221:END,ELEMENTS
222:AXISYM
223:STOP
```

APPENDIX II

```
100 PAGE
110 PRINT "*******SPHERICAL EB MODEL GENERATOR*******"
120 PRINT "JWHICH FILE DO YOU WANT THE DATA TO BE STORED IN?";
130 INPUT D
140 PRINT "JNUMBER OF SHELLS =";
150 INPUT F
160 L=F+1
170 SET RADIANS
180 PRINT "J---------FIRST I.D. POINT---------"
190 PRINT "JSPHERICAL RADIUS 1 =";
200 INPUT R1
210 PRINT "I.D. 1=";
220 INPUT M1
230 X1=M1/2
240 Y1=SQR(R1*R1-X1*X1)
250 PRINT "J----------SECOND I.D. POINT---------"
260 PRINT "JSPHERICAL RADIUS 2 =";
270 INPUT R2
280 PRINT "I.D. 2 =";
290 INPUT M2
300 X2=M2/2
310 Y2=SQR(R2*R2-X2*X2)
320 REM S'S ARE SLOPES & C'S ARE INTERCEPTS
330 S1=(Y1-Y2)/(X1-X2)
340 C1=Y1-S1*X1
350 REM ANGLE FOR .05 END ELMENT
360 Q=ACS(X1/R1)-0.05/R1
370 Y1=R1*SIN(Q)
380 X1=R1*COS(Q)
390 Q=ACS(X2/R2)-0.05/R2
400 Y2=R2*SIN(Q)
410 X2=R2*COS(Q)
420 S2=(Y1-Y2)/(X1-X2)
430 C2=Y1-S2*X1
```

```
440 PRINT "J----------FIRST O.D. POINT-----------"
450 PRINT "O.D. 1=";
460 INPUT M1
470 X1=M1/2
480 Y1=SQR(R1*R1-X1*X1)
490 PRINT "J---------SECOND O.D. POINT----------"
500 PRINT "O.D. 2 =";
510 INPUT M2
520 PAGE
530 X2=M2/2
540 Y2=SQR(R2*R2-X2*X2)
550 S3=(Y1-Y2)/(X1-X2)
560 C3=Y1-S3*X1
570 REM ANGLE FOR .05 END ELEMENT ON OD
580 Q=ACS(X1/R1)+0.05/R1
590 Y1=R1*SIN(Q)
600 X1=R1*COS(Q)
610 Q=ACS(X2/R2)+0.05/R2
620 Y2=R2*SIN(Q)
630 X2=R2*COS(Q)
640 S4=(Y1-Y2)/(X1-X2)
650 C4=Y1-S4*X1
660 REM OUTPUT FORMATTING
670 FIND D
680 SET DEGREES
690 REM SUBROUTINE FOR RADII & ANGLES
700 P=1
710 PRINT "JINSIDE RADIUS=";
720 INPUT R1
730 PRINT "JOUTSIDE RADIUS =";
740 INPUT R2
750 C$=",1,1,1,1,POLAR,0,0"
760 PRINT @33: USING 770:" 2",",",P+1,",","   3",",",P+2,C$
770 IMAGE 2A,A,2D,A,2A,A,2D,18A
780 PRINT @33: USING 790:R1,",",R1,",",R2,",",R2
```

```
790 IMAGE D.3D,A,D.3D,A,D.3D,A,D.3D
800 A=C1
810 B=S1
820 Y=A*B/(B*B+1)
830 X=SQR(Y*Y+(R1*R1-A*A)/(B*B+1))-Y
840 REM Z'S ARE ANGLES
850 Z1=ACS(X/R1)
860 X=SQR(Y*Y+(R2*R2-A*A)/(B*B+1))-Y
870 Z2=ACS(X/R2)
880 REM REPEATING FOR C2 & S2
890 A=C2
900 B=S2
910 Y=A*B/(B*B+1)
920 X=SQR(Y*Y+(R1*R1-A*A)/(B*B+1))-Y
930 Z3=ACS(X/R1)
940 X=SQR(Y*Y+(R2*R2-A*A)/(B*B+1))-Y
950 Z4=ACS(X/R2)
960 REM REPEATING FOR C4 & S4
970 A=C4
980 B=S4
990 Y=A*B/(B*B+1)
1000 X=SQR(Y*Y+(R1*R1-A*A)/(B*B+1))-Y
1010 Z5=ACS(X/R1)
1020 X=SQR(Y*Y+(R2*R2-A*A)/(B*B+1))-Y
1030 Z6=ACS(X/R2)
1040 REM REPEATING FOR C3 & S3
1050 A=C3
1060 B=S3
1070 Y=A*B/(B*B+1)
1080 X=SQR(Y*Y+(R1*R1-A*A)/(B*B+1))-Y
1090 Z7=ACS(X/R1)
1100 X=SQR(Y*Y+(R2*R2-A*A)/(B*B+1))-Y
1110 Z8=ACS(X/R2)
1120 PRINT @33: USING 1130:Z1,",",Z3,",",Z4,",",Z2
1130 IMAGE 2D.3D,A,2D.3D,A,2D.3D,A,2D.3D
```

```
1140 PRINT @33: USING 770:" 3",",",P+1,",","13",",",P+2,C$
1150 PRINT @33: USING 790:R1,",",R1,",",R2,",",R2
1160 PRINT @33: USING 1130:Z3,",",Z5,",",Z6,",",Z4
1170 PRINT @33: USING 770:"13",",",P+1,",","14",",",P+2,C$
1180 PRINT @33: USING 790:R1,",",R1,",",R2,",",R2
1190 PRINT @33: USING 1130:Z5,",",Z7,",",Z8,",",Z6
1200 P=P+2
1210 G=2*L+1
1220 IF P=G THEN 1300
1230 IF P=9 THEN 1270
1240 IF P=15 THEN 1270
1250 IF P=21 THEN 1270
1260 GO TO 710
1270 PAGE
1280 GO TO 710
1290 CLOSE
1300 END
```

APPENDIX III

NOMENCLATURE

K = A linear spring rate.

K_T = A torsional spring rate.

d = The differential operator.

A = Area.

G = The shear modulus.

T = Torque.

t = The perpendicular layer thickness.

R = The spherical radius.

$\overline{R}$ = The moment arm or distance to the bearing axis.

$\overline{R}_o$ = The largest moment arm in a layer.

H = The axial distance from a point to the spherical axis.

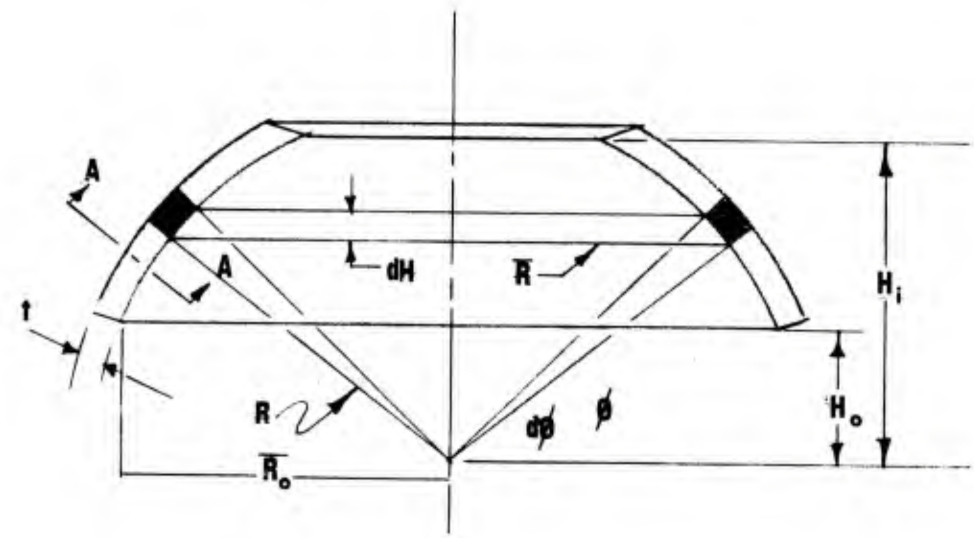
H_o = The axial distance of the O.D. of a layer to the spherical axis.

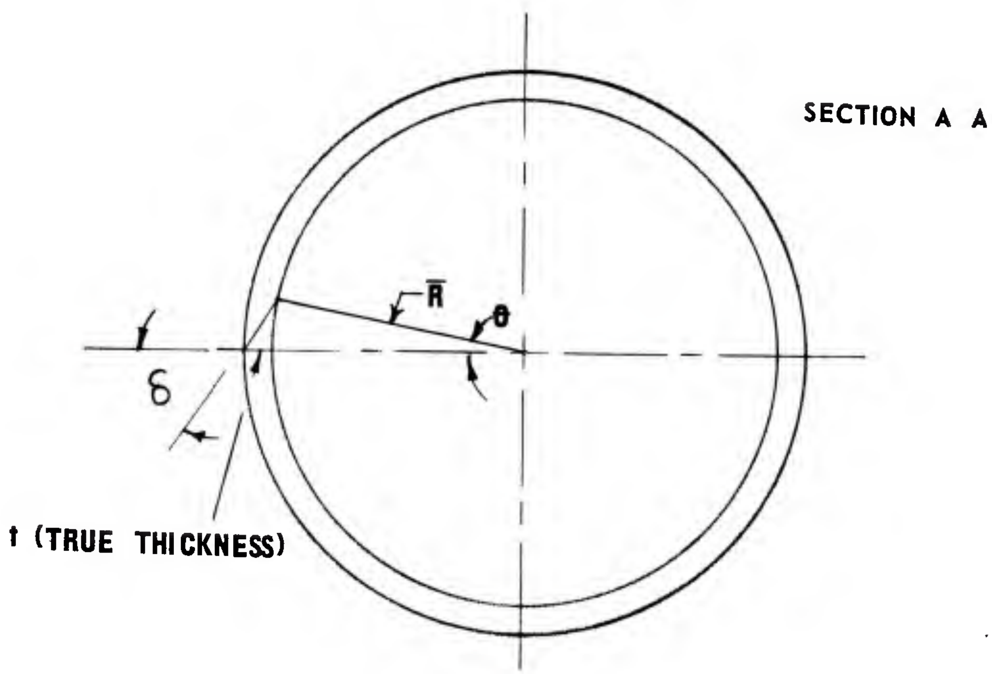
H_i = The axial distance of the I.D. of a layer to the spherical axis.

θ = The torsional angle of relative rotation for the layer.

ϕ = An arbitrary angle of integration.

γ = The shear strain.





AXIAL TORSION ON A POLAR SPHERICAL E.B.

AXIAL TORSION ON A POLAR SPHERICAL E.B.

The shear spring rate of an elastomeric layer is

$$K = F/\delta = \frac{GA}{t}$$

For a layer with constant thickness and modulus the rate of change of spring rate is

$$dK = (G/t)dA$$

The rate of change in torsional rate is

$$dK_T = \frac{G\overline{R}^2}{t} \quad dA$$

The differential area for a polar spherical layer (See Figure) is

$$dA = 2\pi\overline{R}Rd\phi$$

$$\phi = SIN^{-1}(H/R)$$

$$d\phi = \frac{dH}{\sqrt{R^2 - H^2}}$$

$$\overline{R} = \sqrt{R^2 - H^2}$$

$$dA = 2\pi RdH$$

Substituting in the spring rate equation

$$dK_T = \frac{2\pi GR}{t} (R^2 - H^2)dH$$

$$K_T = \frac{2\pi GR}{t} \int_{H_i}^{H_o} (R^2 - H^2)dH$$

$$K_T = \frac{2\pi GR}{t} \left[R^2(H_i - H_o)-(H_i^3 - H_o^3)/3\right]$$

The definition of torsional spring rate is

$$K_T = T/\theta$$

The shear strain (See Figure) is

$$\gamma = \frac{\bar{R}\theta}{t}$$

$$\gamma = \frac{\bar{R}T}{tK_T}$$

$$\gamma = \frac{T\sqrt{R^2 - H^2}}{tK_T}$$

$$\gamma = \frac{T\sqrt{R^2 - H^2}}{2\pi GR}\left[\frac{1}{R^2(H_i - H_o)-(H_i^3 - H_o^3)/3}\right]$$

The pitch change shear strain is seen to be a function of position but, has a maximum at the O.D. of each layer of

$$\gamma_{MAX.} = \frac{T}{2\pi G}\left[\frac{\sqrt{1 - (H_o/R)^2}}{R^2(H_i - H_o)-(H_i^3 - H_o^3)/3}\right]$$

The composite rotation for a multi-layer bearing is

$$\theta = \Sigma\,\frac{t\gamma_{MAX.}}{\bar{R}_o}$$

$$= \frac{T}{2\pi}\,\Sigma\,\frac{1}{GR}\left[\frac{t}{R^2(H_i - H_o)-(H_i^3 - H_o^3)/3}\right]$$

A P P E N D I X   IV

```
100 PAGE
110 INIT
120 PRINT "************ PITCH CHANGE STRAIN CALCULATIONS ************"
130 PRINT "****** for spherical EB with 2 different elastomers ******"
140 PRINT "layer no. from mushroom end at which elastomer changes---";
150 INPUT L
160 PRINT "JFIRST SHEAR MODULUS,G1----";
170 INPUT G1
180 PRINT "SECOND SHEAR MODULUS,G2---";
190 INPUT G2
200 PRINT "NUMBER OF SHELLS----------";
210 INPUT J
220 PRINT "JAPPLIED TORQUE = ";
230 INPUT T
240 DIM F(50),P(50),R1(50),V(50)
250 PRINT "J------------ FIRST I.D POINT ------------"
260 PRINT "JSPHERICAL RADIUS 1 = ";
270 INPUT R
280 PRINT "I.D. 1 = ";
290 INPUT M1
300 X1=M1/2
310 Y1=SQR(R*R-X1*X1)
320 PRINT "J----------- SECOND I.D. POINT -----------"
330 PRINT "JSPHERICAL RADIUS 2 = ";
340 INPUT R2
350 PRINT "I.D. 2 = ";
360 INPUT M2
370 X2=M2/2
380 Y2=SQR(R2*R2-X2*X2)
390 REM S'S ARE SLOPES & C'S ARE INTERCEPTS
400 S1=(Y1-Y2)/(X1-X2)
410 C1=Y1-S1*X1
420 PRINT "J------------ FIRST O.D. POINT -----------"
430 PRINT "O.D. 1 = ";
```

```
440 INPUT M1
450 X1=M1/2
460 Y1=SQR(R*R-X1*X1)
470 PRINT "J----------- SECOND O.D. POINT -----------"
480 PRINT "O.D. 2 = ";
490 INPUT M2
500 X2=M2/2
510 PAGE
520 Y2=SQR(R2*R2-X2*X2)
530 S2=(Y1-Y2)/(X1-X2)
540 C2=Y1-S2*X1
550 I=1
560 G=G1
570 PRINT "INSIDE SPHERICAL RADIUS OF THE LAYER CONSIDERED";
580 INPUT R1(I)
590 Z=C1*S1/(S1*S1+1)
600 X=SQR(Z*Z+(R1(I)*R1(I)-C1*C1)/(S1*S1+1))-Z
610 H1=C1+S1*X
620 REM REPEATING FOR C2 & S2
630 Z=C2*S2/(S2*S2+1)
640 X=SQR(Z*Z+(R1(I)*R1(I)-C2*C2)/(S2*S2+1))-Z
650 H2=C2+S2*X
660 D=R1(I)*R1(I)*(H1-H2)-(H1↑3-H2↑3)/3
670 U=SQR(1-(H1/R1(I))↑2)
680 F(I)=U*T/(D*2*PI*G)
690 PRINT "VERTICAL THICKNESS OF THE LAYER = ";
700 INPUT V(I)
710 P(I)=90*V(I)*T/(PI*PI*G*D*R1(I))
720 IF I<=L-1 THEN 740
730 G=G2
740 I=I+1
750 IF I<J+2 THEN 570
760 K=0
770 PAGE
780 PRINT USING "70""-""":
```

```
790 PRINT "                PITCH CHANGE PARAMETERS"
800 PRINT USING "70""-""":
810 PRINT USING 820:"NO.","LAYER","INSIDE","GAMMA","THETA"
820 IMAGE3T,FA,10T,FA,21T,FA,31T,FA,41T,FA,
830 PRINT USING 820:"     ","THICK","RADIUS","STRAIN","LAYER"
840 PRINT USING "70""-""":
850 K=0
860 FOR I=1 TO J+1
870 K=K+P(I)
880 PRINT USING 890:I,V(I),R1(I),F(I),P(I)
890 IMAGE 3T,2D,10T,D.3D,21T,D.3D,31T,D.4D,41T,D.4D
900 NEXT I
910 PRINT USING "70""-""":
920 PRINT "JTOTAL ANGLE OF TWIST IN DEGREES (THETA)----";
930 PRINT K
940 PRINT "JAPPLIED TORQUE IN LB.-INCHES---------------";
950 PRINT T
960 END
```

SECTION 9.

TEST RESULTS ON THE BLACKHAWK MAIN ROTOR BEARINGS

Enclosed in the Appendix is a test report covering the testing of a pair of Blackhawk main rotor sperical and thrust elastomeric bearings as outlined in Section 1. These results should be correlated with previous analytical results.

The agreement between experimental and analytical predictions is reasonably good for the thrust bearing. See that Figures 4 and 5 of the Appendix confirm the location of first damage predicted in Section 6. The analytical prediction of time to first damage was 46 hours, whereas, first damage was actually reported as occurring between 200 and 300 hours. The test substantiated the analytical prediction that elastomer damage would occur before metal fatigue.

For the spherical bearing the agreement between experimental and theoretical predictions is again reasonably good for the elastomer. Photograph 2 shows the I.D. of the first layer as the location of first damage. The I.D. of the fourth layer is the location predicted in Section 8. The first damage life was between 300 and 400 hours vs. a predicted 866 hours. Remember that no prediction of the endurance life of the metal shells could be made in section 8.

It is important to recognize that "first damage" as defined here is the first sign of damage visible under laboratory conditions and that elastomer damage in an elastomeric bearing is slowly progressive and noncatastrophic. The justification for this statement is Sikorsky Aircraft's 2000 hr. qualification test with these bearings. While laboratory level damage was observed on these bearings relatively early in the test they continued on for from 10 to 20 times the laboratory first damage life shown here without excessive damage.

A P P E N D I X

CR INDUSTRIES

TEST REPORT

AMMRC Contract DAA-46-78-C-0029

May 22, 1979

By

Emmet M. Skroch

Test Lab Manager

TEST REPORT

This test consisted of endurance testing two Blackhawk Main Rotor Elastomeric Bearings per the plan described in the AMMRC test proposal of September 15, 1978.

Prior to any endurance testing all samples were acceptance tested according to their respective Sikorsky approved ATP's (ATP No. 4014 for 80 9588, Sikorsky SB7001-045 and ATP No. 4015 for 80 9589, Sikorsky SB7002-045).

For the spherical bearings (P/N 80 9588), slight modification to the end fitting had to be made (Figure 1.1) to fixture them in our test rig (Figure 1.2). Thermocouples were attached at the 6 o'clock and 9 o'clock position, both inside and outside, at the inner race. For the thrust bearing (P/N 80 9589), a thermocouple was attached to the outer center part of the bearing.

All loads and motions of the test were applied in 100 hour blocks as specified in the Blackhawk Main Rotor E. B. Endurance Life Test Blocks I through III.

Testing of the spherical bearing (P/N 80 9588), has been terminated after a total of 4 blocks of testing or 400 flight hours. First damage was observed at the first rubber layer (smallest spherical radius) at the 5 and 11 o'clock positions when flapping was applied through the 6 and 12 o'clock axis. Figures 2 and 3 show the degree of damage of each bearing. The recorded temperatures of the test ranged from 91°F to 109°F.

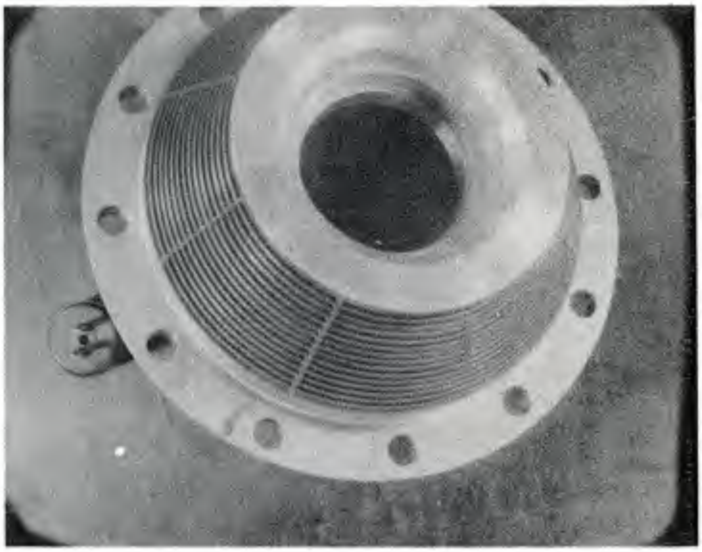
The loss of measured axial spring rates ranged from 2.4% to 3.4% for the 400 flight hour period.

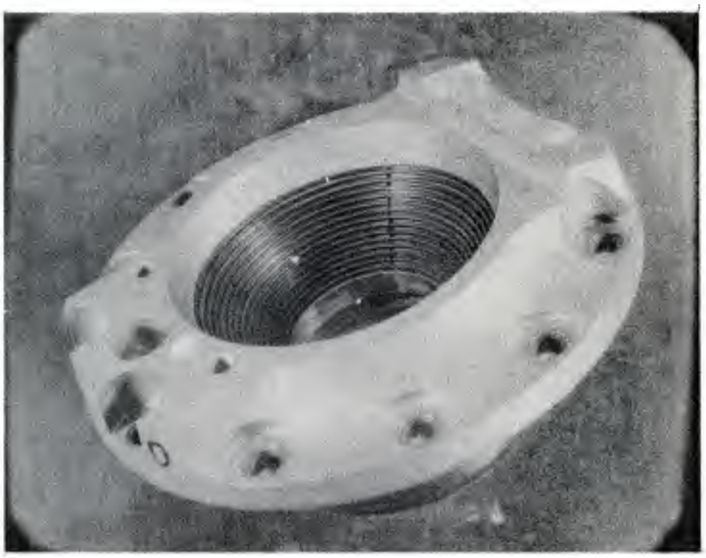
Testing of the thrust bearing (P/N 80 9588) has been terminated after a total of 3 blocks of testing or 300 flight hours. First damage was observed at the O.D. of the bearing on the spline side and at the I.D. on the flanged side. Figures 4 and 5 show the degree of the damage.

The recorded temperatures during the test ranged from 116°F to 120°F. The loss of measured axial spring rates for the two bearings was as follows:

% Spring Rate Change

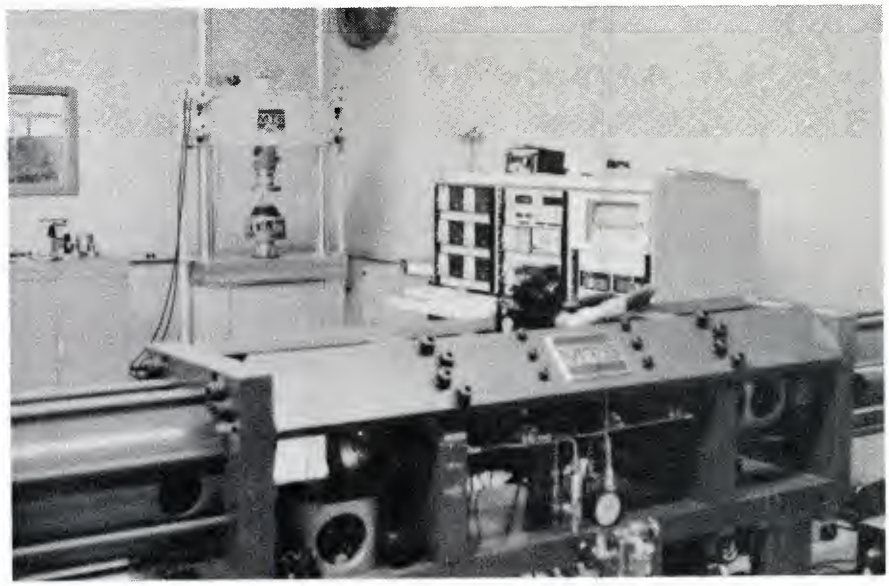
Flight Hours	SN 00049	SN 00051
New	-	-
200	1.3	2.6
300	1.3	5.1

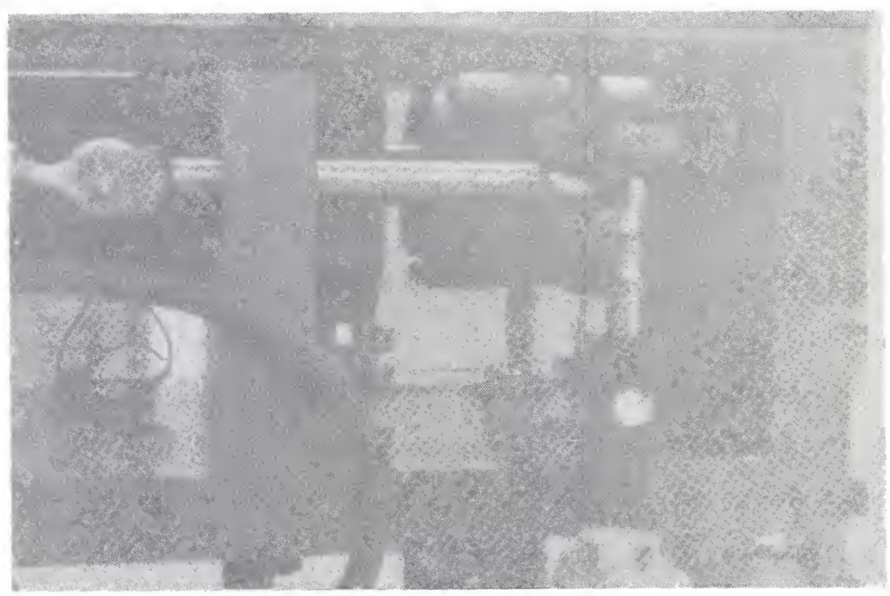




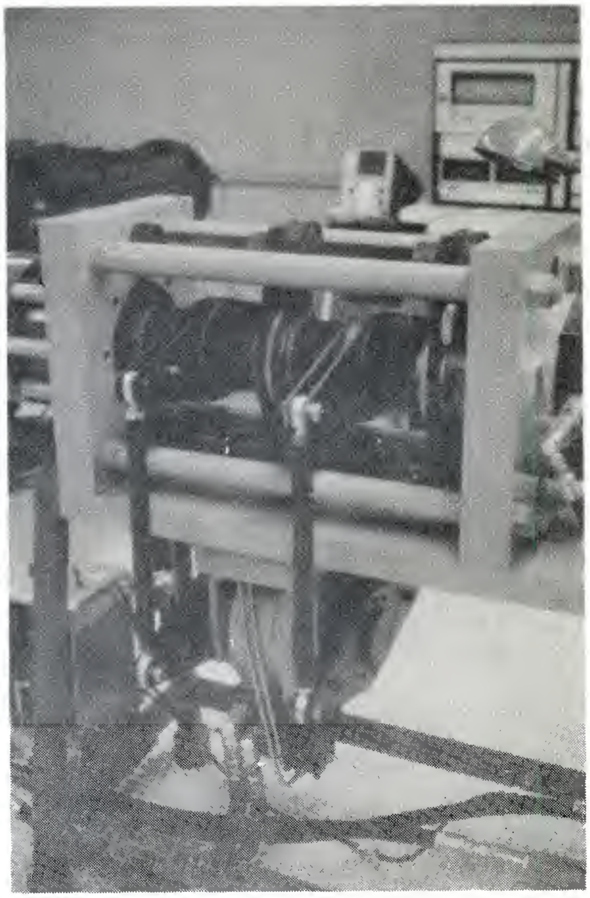
MODIFIED SPHERICAL BEARING

FIGURE 1.1

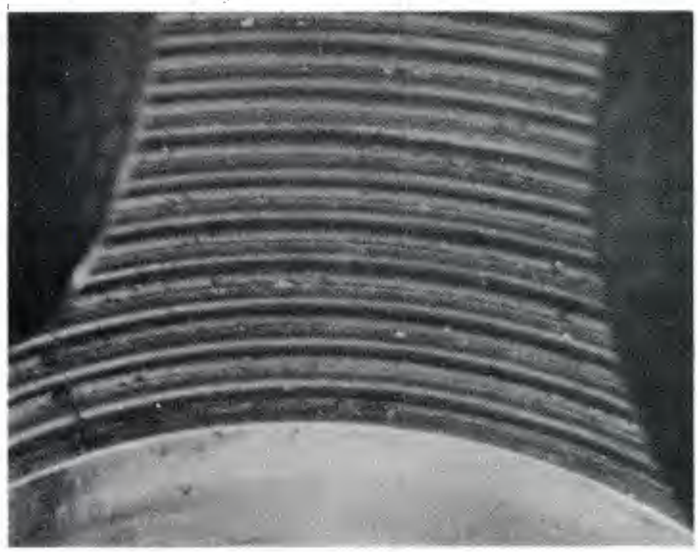


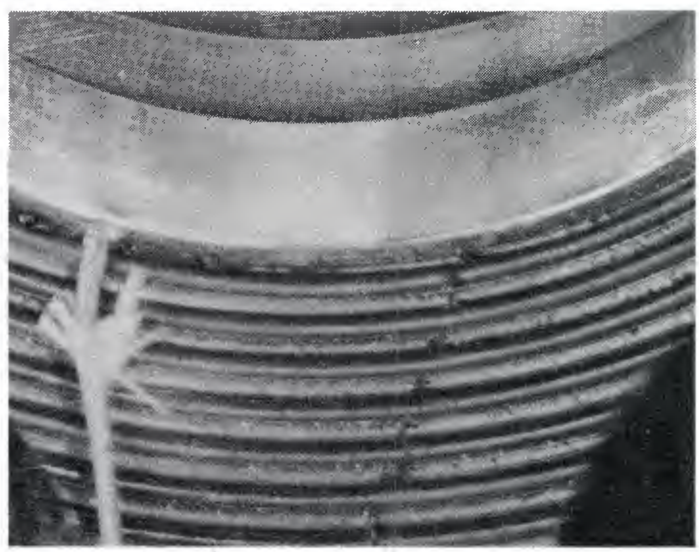


SPHERICAL BEARING
TEST RIG.
FIGURE 1.2



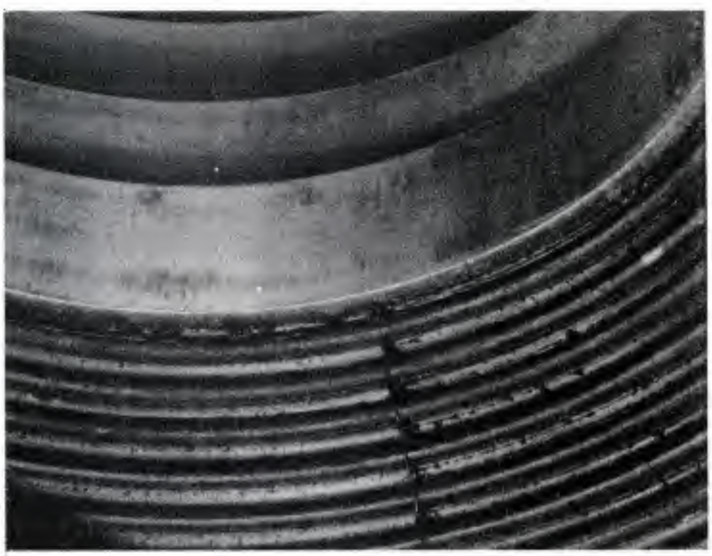
THRUST BEARING
TEST RIG.
FIGURE 1.3





C.R. 80 9588 (SN 00005) SPHERICAL BEARING I.D. AFTER 400 FLIGHT HOURS.

FIGURE 2

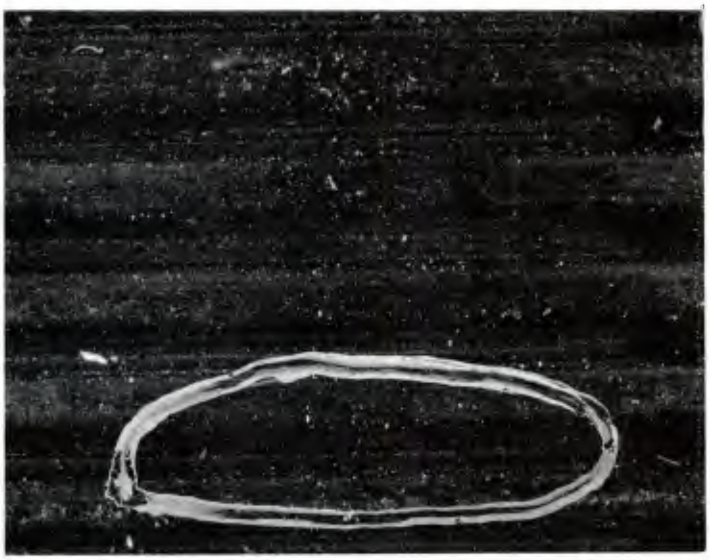


C.R. 80 9588 (SN 00004) SPHERICAL BEARING I.D. AFTER 400 FLIGHT HOURS.

FIGURE 3

THRUST BEARING I.D.

FIGURE 4



THRUST BEARING O.D.

FIGURE 5

SECTION 10.

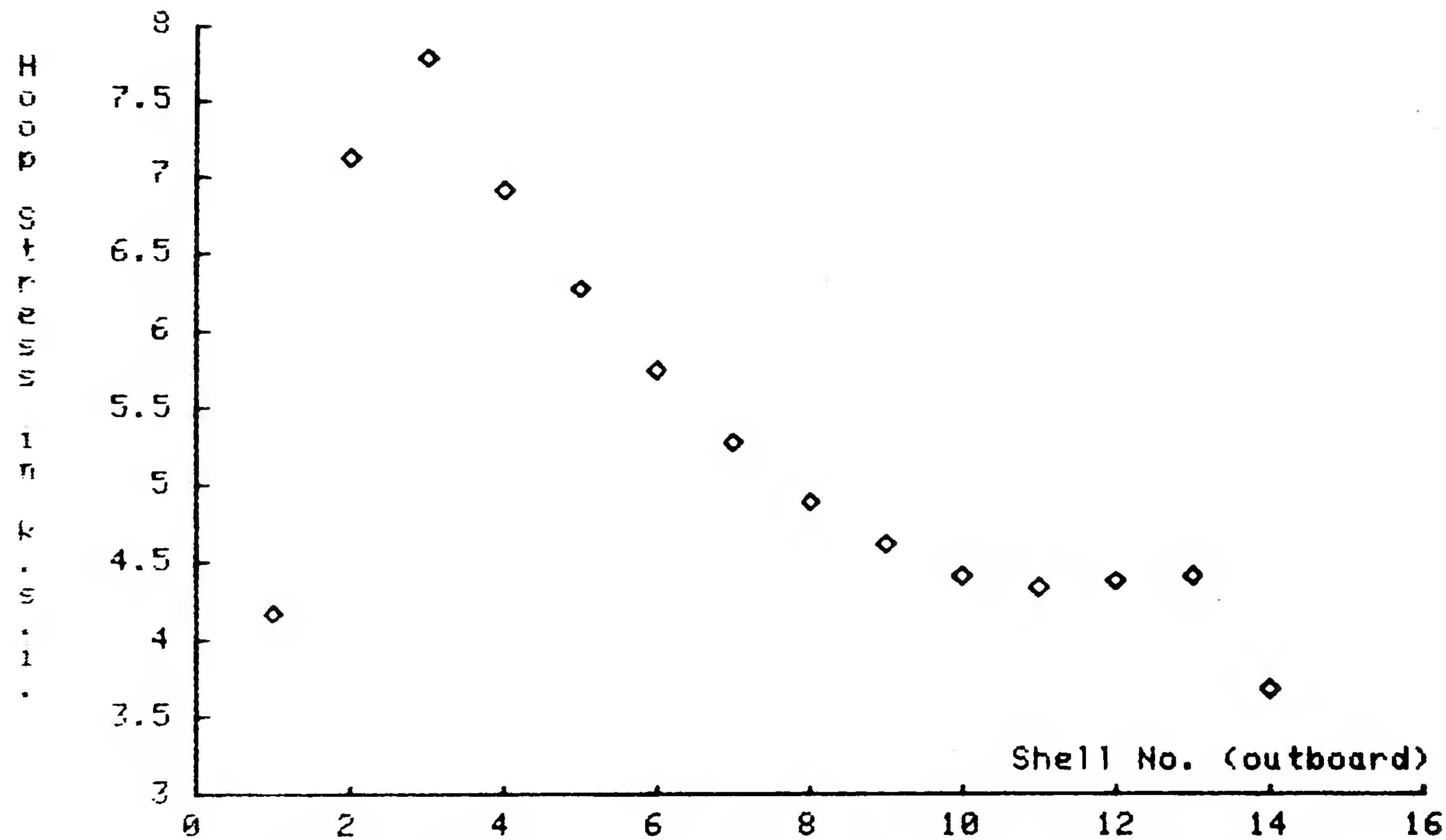
TEST RESULTS ON THE BLACKHAWK MAIN ROTOR SPHERICAL BEARING WITH ON-OFF CENTRIFUGAL FORCE AS THE ONLY LOADING MODE

In order to obtain some correlation between analytical and experimental results for shell stress in a spherical bearing, a sample was tested with on-off centrifugal force as the only loading (see test report in the Appendix). This test case can be completely analyzed by one program run of our quasi three-dimensional finite element analysis program. Fig. 1 shows the shell stress at the I.D. for this loading case and Fig. 2 shows it for the O.D. This loading case is not expected to produce failure in the 17-7 PH stainless steel shells. Shell failure was not observed in this test.

From results in Section 8, the predicted elastomer life under this loading condition is

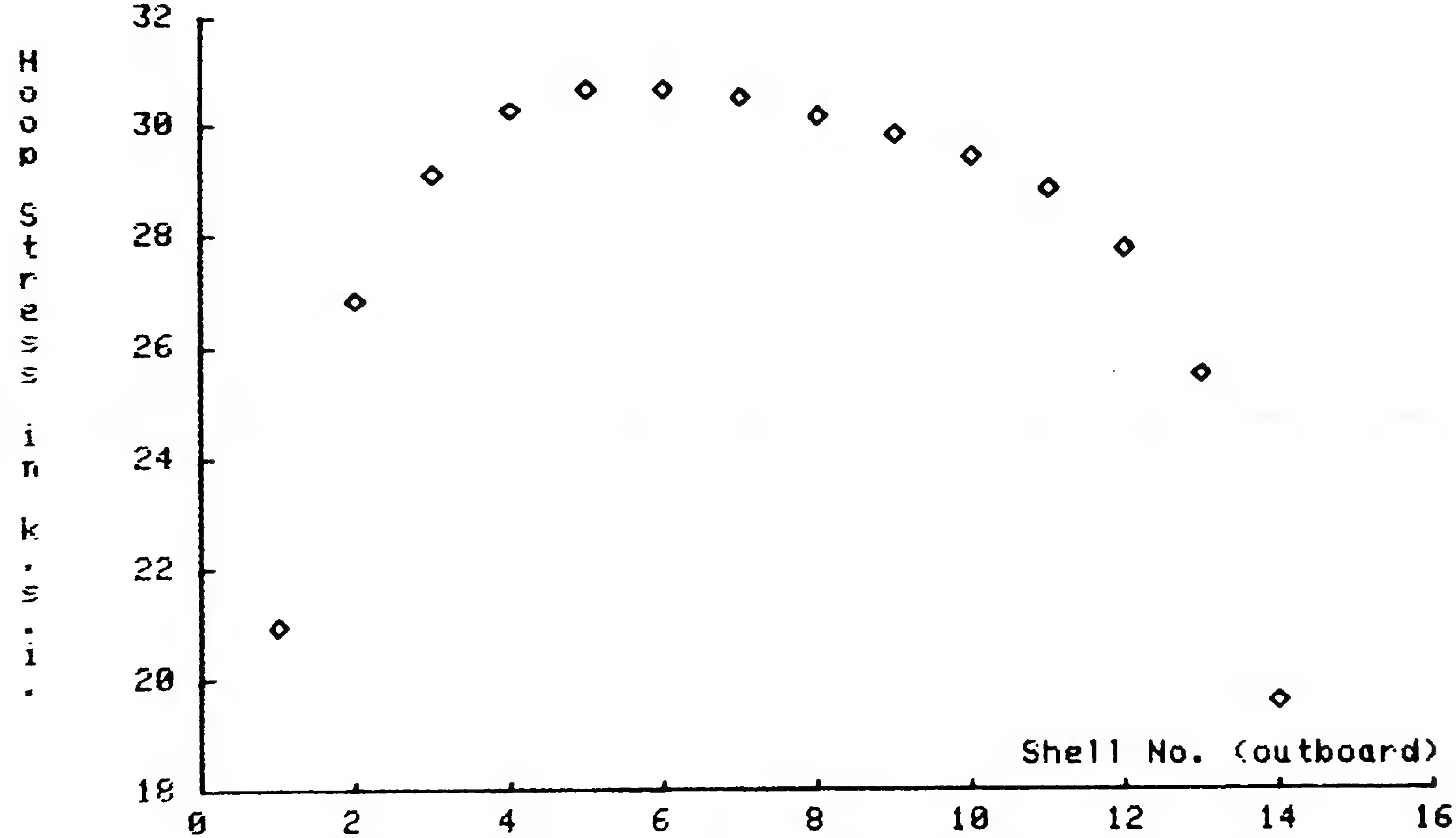
$$\left(\frac{10.6}{2.95/2}\right)^5 = 19{,}200 \text{ cycles}$$

with first damage predicted for the I.D. of the fourth layer. First damage was experimentally noted at 55,000 cycles at the bearing I.D. in the zone of the 3rd to 5th layers.



STRESS ALONG I.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
AT 68,000 LBS. AXIAL LOAD.
11/28/79

FIG. 1



STRESS ALONG O.D. FOR AMMRC SPHERICAL EB (14 SHELLS)
AT 68,000 LBS. AXIAL LOAD.
11/28/79

FIG. 2

APPENDIX

Chicago Rawhide Mfg. Co., 2517 Pan Am Blvd., Elk Grove Village, Ill. 60007, 312/595-4620

CR INDUSTRIES

Test Report

AMMRC Contract DAA-46-78-C-0029

May 29, 1979

by

Emmet M. Skroch

Test Lab Manager

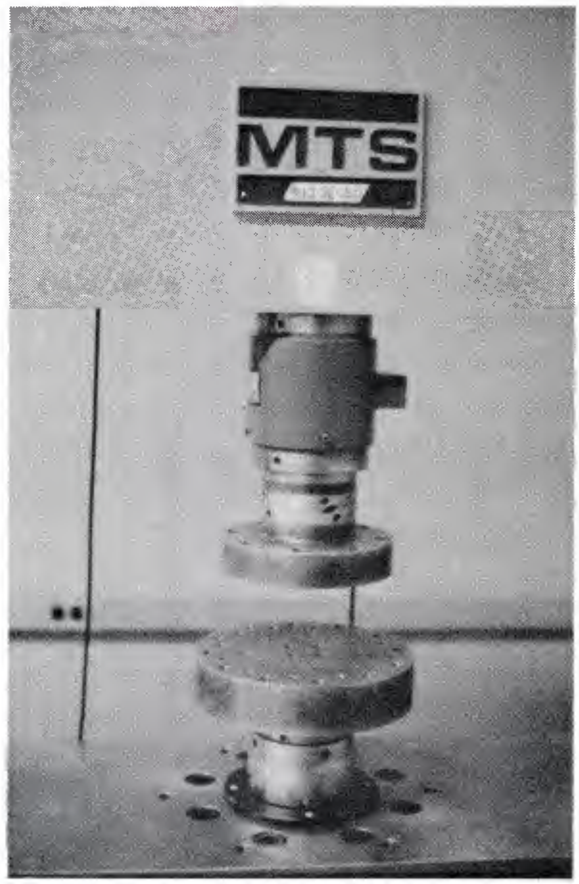
Test Report

This test consisted of endurance testing a Blackhawk Main Rotor Elastomeric Bearing by "on-off" C.F. loading.

Prior to any endurance testing, the sample was acceptance tested according to its' respective Sikorsky approved ATP (ATP No. 4014 for 80 9588, Sikorsky SB7001-045).

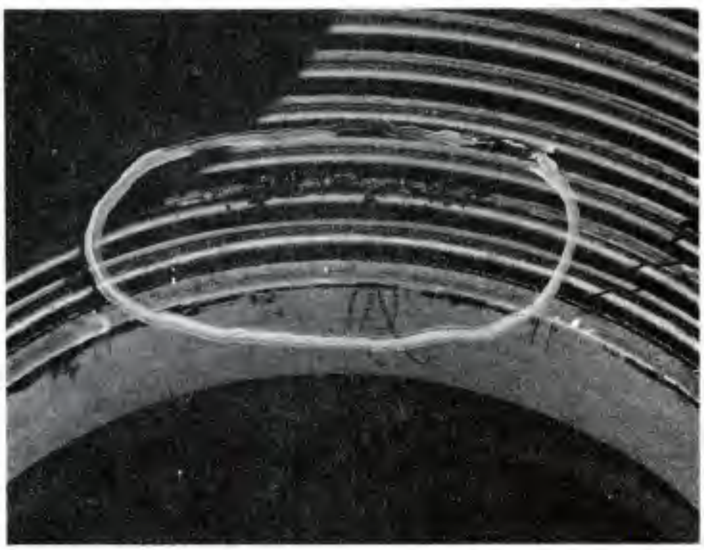
A spherical bearing (P/N 80 9588) was axially loaded and unloaded from 0 to 68,000 lbs. at a cycling rate of 20 cycles per minute (CPM). The test part was loaded in our 100 KIP test rig, see Figure 1.

First damage was observed after 55,000 on-off cycles or the equivalent of 27,500 flight hours as described in the AMMRC test proposal of September 15, 1978, Black Hawk Rotor E.B. Endurance Life Test Block III. The damaged area consisted of the first 10 elastomeric layers (smallest spherical radius being the 1st layer) at the I.D., in varying degree. Figure 2 shows the predominant damage which occurred in the zone of the 3rd through 5th layers.



AXIAL TEST RIG

FIGURE 1



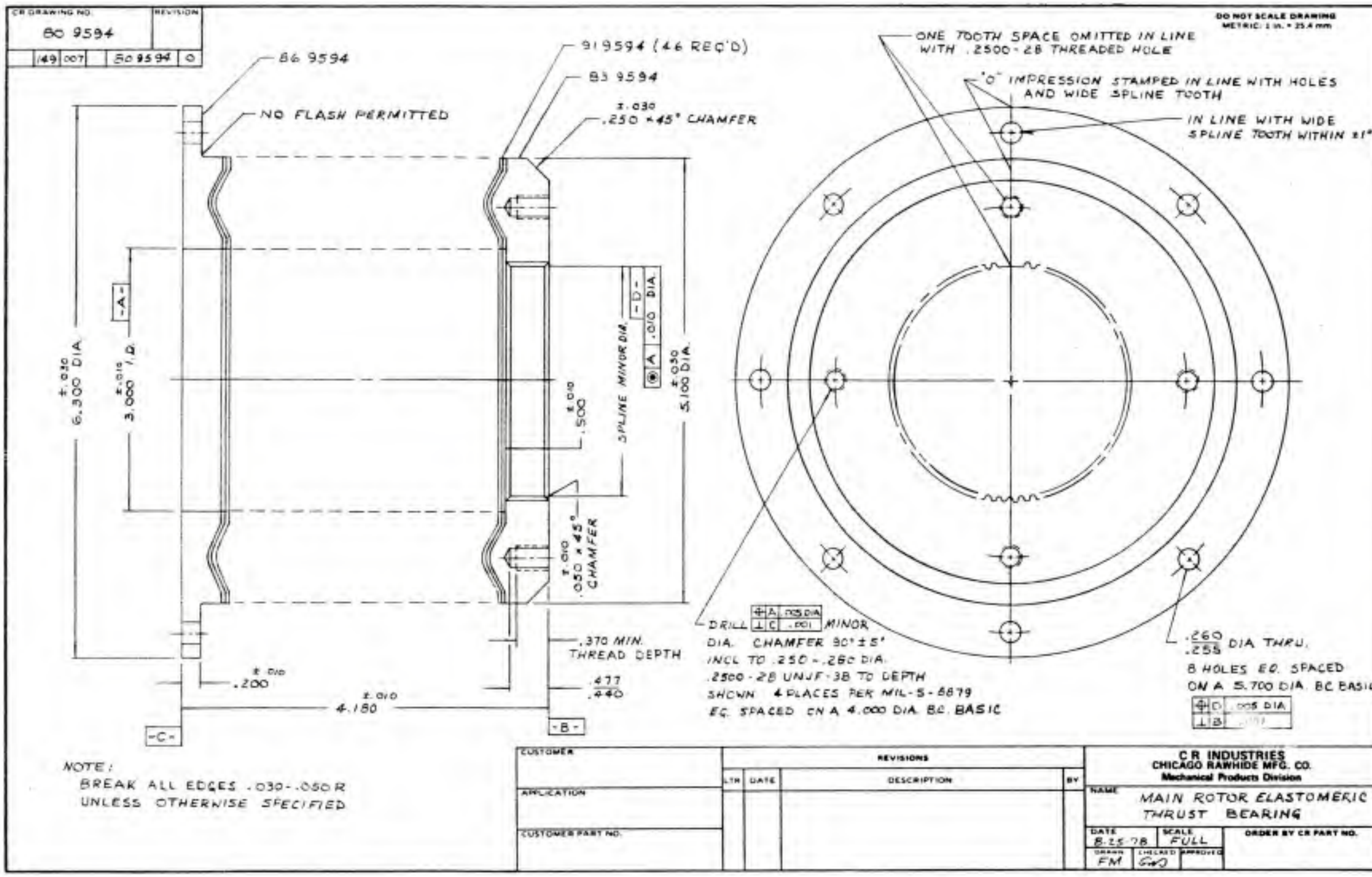
I.D. OF 80 9588 (SPHERICAL BEARING)

FIGURE 2

SECTION 11.

TEST RESULTS ON THE ALTERNATE BLACKHAWK MAIN ROTOR THRUST BEARING WITH ON-OFF CENTRIFUGAL FORCE AS THE ONLY LOADING MODE.

In order to demonstrate the ability of finite element analysis to predict the endurance life of the metal shells in laminate elastomeric bearings a marginal bearing design was analyzed in Section 7 (see Fig. 1) and tested. The test report is included in the appendix. The analysis of this test case did not require the use of superposition. The correlation between analytic and test results should, therefore, be good. The correlation between analytic and test results is seen to be good -- the shells cracked about as predicted.



CR DRAWING NO. 80 9594
REVISION 0
DO NOT SCALE DRAWING
86 9594
NO FLASH PERMITTED
919594 (46 REQ'D)
83 9594
±.030 .250 × 45° CHAMFER
ONE TOOTH SPACE OMITTED IN LINE WITH .2500-28 THREADED HOLE
"0" IMPRESSION STAMPED IN LINE WITH HOLES AND WIDE SPLINE TOOTH
IN LINE WITH WIDE SPLINE TOOTH WITHIN ±1°
±.030 6.300 DIA.
±.010 3.000 I.D.
-A-
±.010 .500
SPLINE MINOR DIA.
-D-
±.030 5.100 DIA.
±.010 .050 × 45° CHAMFER
.370 MIN. THREAD DEPTH
.477 .440
±.010 .200
±.010 4.180
-C-
-B-
DRILL MINOR DIA. CHAMFER 90° ± 5° INCL TO .250-.260 DIA. .2500-28 UNJF-3B TO DEPTH SHOWN 4 PLACES PER MIL-S-8879 EQ. SPACED ON A 4.000 DIA. BC. BASIC
.260 .255 DIA THRU. 8 HOLES EQ. SPACED ON A 5.700 DIA. BC BASIC
NOTE: BREAK ALL EDGES .030-.050 R UNLESS OTHERWISE SPECIFIED
CUSTOMER
APPLICATION
CUSTOMER PART NO.
REVISIONS
LTR DATE DESCRIPTION BY
C R INDUSTRIES
CHICAGO RAWHIDE MFG. CO.
Mechanical Products Division
NAME MAIN ROTOR ELASTOMERIC THRUST BEARING
DATE 8-25-78
SCALE FULL
DRAWN FM
ORDER BY CR PART NO.

FIG. 1

APPENDIX

CHICAGO RAWHIDE MANUFACTURING COMPANY

July 2, 1979

FINAL TEST REPORT

AMMRC - Chevron Washer SK5-80 9590 — Thrust Bearing H90112-1

The bearing tested January 17-19, 1979 was pulled to destruction and then soaked in toluene to remove the rubber and observe the washers.

In the layer that broke in the pull test, about 80% of the rubber was destroyed by fatigue damage. The pull test values were:

	Test Piece	Control Piece
Breaking Load	1,400 lbs.	8,200 lbs.
Extension	0.1 in.	0.15 in.
Mode of Failure	100R	90R 10 unfill

The cleaned washers were examined for cracks. (Flange end-1-52-Spline end)

One radial crack in washer #22 intersected the O.D..

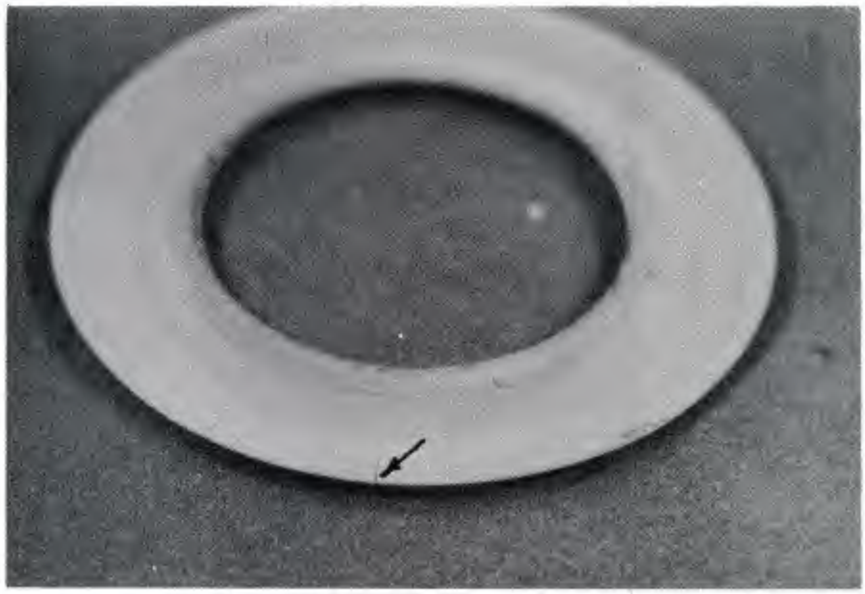
Nine washers exhibited tangential cracks along the top of the chevron. (#13, 18, 19, 20, 23, 24, 27, 29, 38)

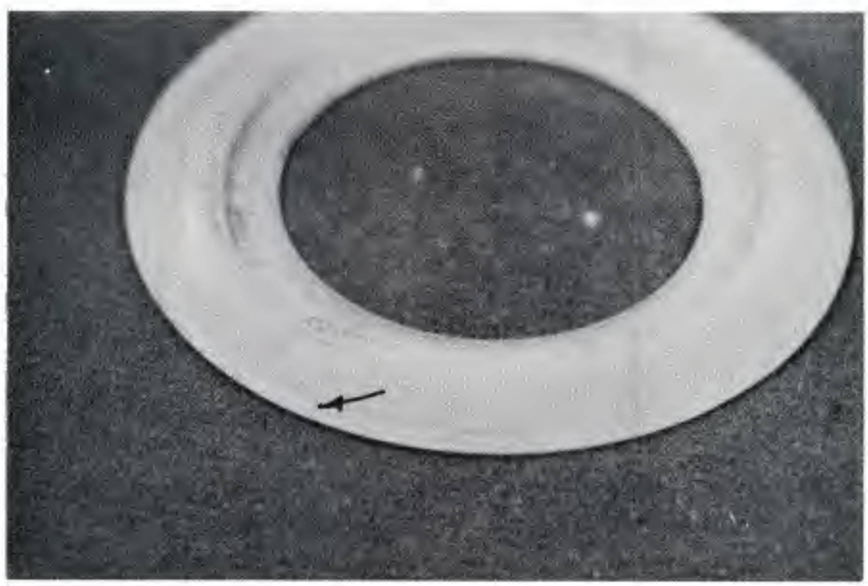
Photographs of the cracked washers are attached.

Tom Mueller

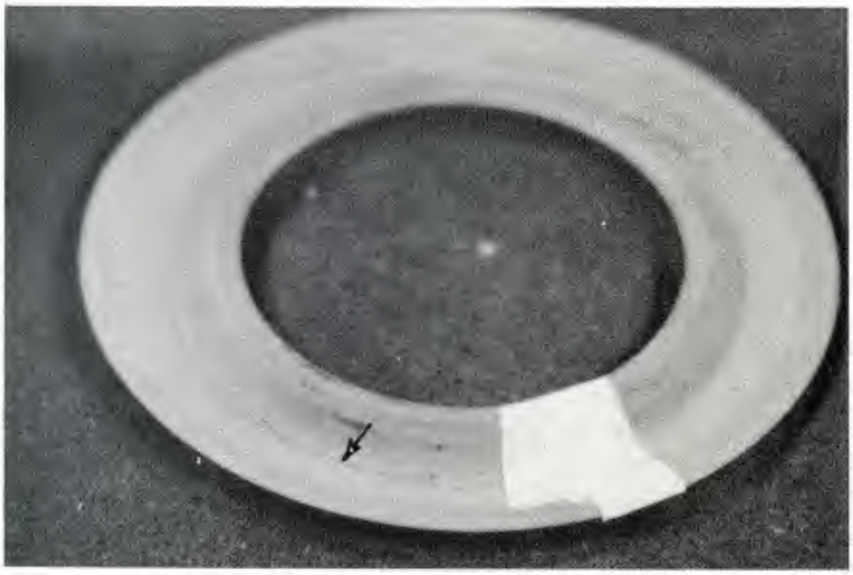
Tom Mueller

TM:lk
Enclosures

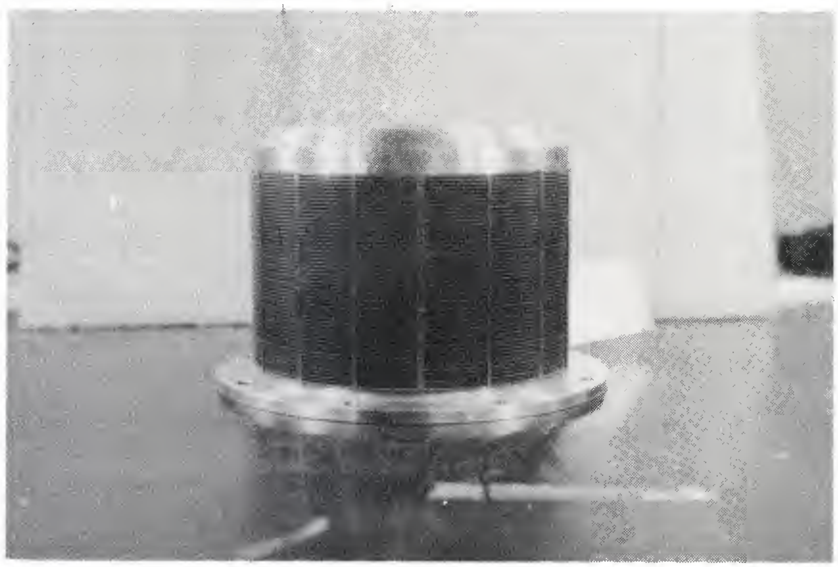




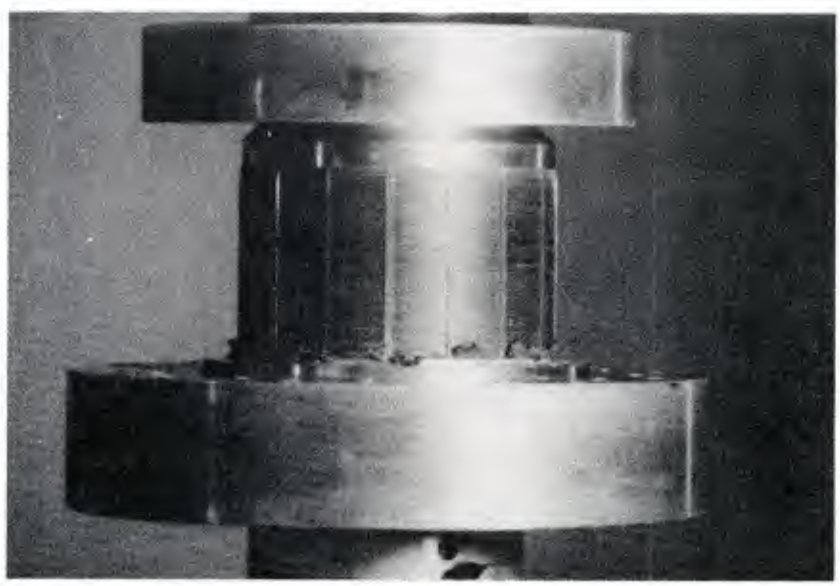
RADIAL CRACK



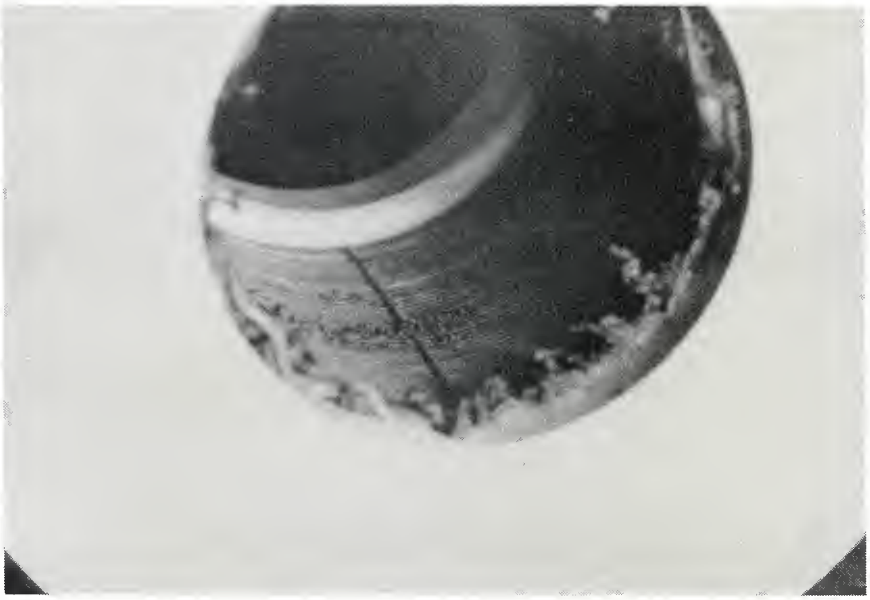
TANGENTIAL CRACK



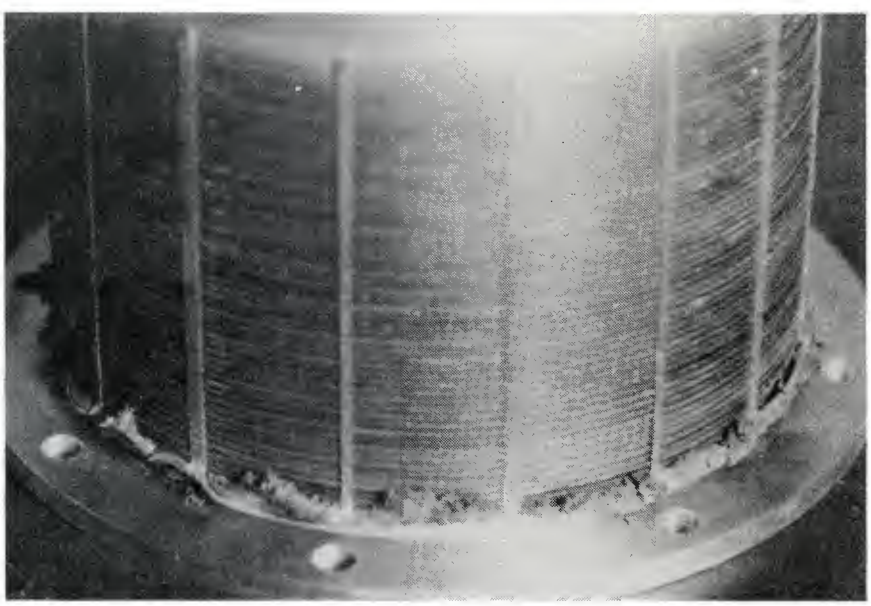
BEFORE



AFTER



I.D. DAMAGE



O.D. DAMAGE

O.D. CRACK

CHICAGO RAWHIDE MANUFACTURING COMPANY

January 23, 1979

TEST REPORT

AMMRC - Chevron Washer SK5-80 9590 | Thrust Bearing H90112-1

Test Start: 2:00 P.M. January 17, 1979
Stop: 7:46 P.M. January 19, 1979

At 51,300 GAG cycles a cracked washer was observed on the O.D. of the bearing.

The last inspection prior to the observation of the crack was at 45,800 GAG cycles.

A "clicking" sound was heard about the 43,000 cycle mark and went away.

The test has been stopped to get photographs of the cracked washer and to decide on further actions to be taken.

A table of axial spring rates is attached.

Tom Mueller

Tom Mueller

TM:lk
Enclosure

cc: J. Morley
A. Hatch
E. Skroch

SK5-80 9590
H90112-1

Axial Spring Rate

# Cycles	Deflection to 68,000 # Inches	40,000-68,000 # Lbs./In.	Tangent 68,000 # Lbs./In.
0	0.100	933,000	1,000,000
15,000	0.110	830,000	1,000,000
25,000	0.112	830,000	950,000
30,000	0.115	830,000	950,000
45,000	0.115	830,000	890,000
50,000	0.115	830,000	890,000

Initial Ht.	50,000~	ΔHT
4.202	4.180	.022

T.G.M.
1-23-79

The initial Chevron Washer Endurance Test for the AMMRC Contract was started at 2:00 P.M. January 17, 1979.

The test is running with the following parameters:

1.	Cyclic axial load	100/68,000/100 lbs.
2.	Frequency	20 cpm.
3.	Length of test	Until washer failure observed.
4.	Inspection period	At least twice daily.
5.	Documentation	Color photographs a) Initial condition. b) At point of washer failure.

This is a modified SK5-80 9590 thrust bearing molded in the 80 9589 mold with modifications. It has 52 Titanium A70 washers of .030 thickness and .245 radius (see drawing attached). The end fittings are steel.

The bonding process on the Titanium was done per P-7554, which is the current production process on the Sikorsky main rotor bearings for Titanium.

Weight: 9.25#
Height: 4.202 in.

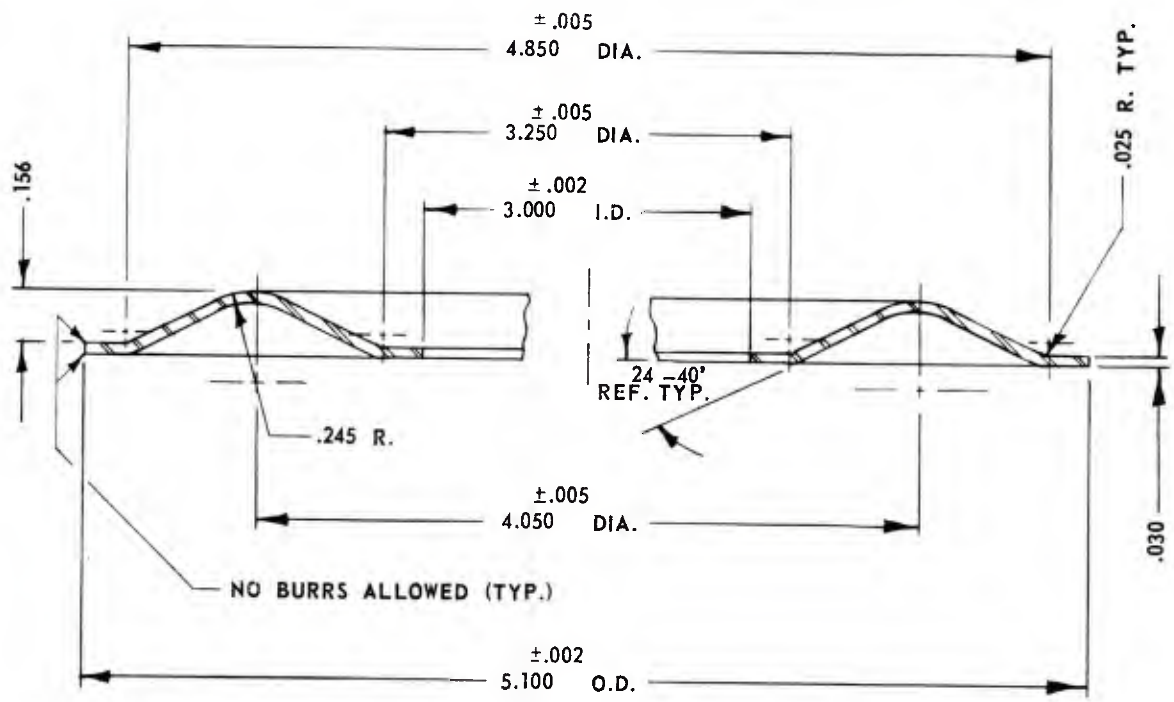
Tom Mueller

Tom Mueller

TM:lk

cc: J. Morley, A. Hatch, E. Skroch

DISPOSITION:	REVISIONS					
	LTR	DESCRIPTION	DATE	DRAWN	CHK	APPR



NOTES:

1. I.D. & O.D. MUST BE CONCENTRIC WITHIN .003 T.I.R.
2. MUST BE FLAT WITHIN .005 T.I.R.

USED IN DL:	METRIC: 1 IN. = 25.4 mm	MATERIAL	C R INDUSTRIES
	UNLESS OTHERWISE SPECIFIED DIAMETER ± .010 HEIGHTS ± .005 DRILLED HOLES + .010 – .000 BREAK SHARP EDGES .005 TO .015 REMOVE ALL BURRS FINISH ALL OVER R.M.S. CONCENTRIC WITHIN .005 T.I.R. CORNER FILLETS .005 __ .015 R. ANGLES ± 30'	TITANIUM AMS 4901 OR ASTM B265 GRADE 4	CHICAGO RAWHIDE MFG. CO. Mechanical Products Division NAME: WASHER SCALE: 2x DATE: 8-3-78 CR DWG. NO. SK 5-91 9590 REV. DRAWN BY: RZ CHECKED: GL APPROVED: AT

SECTION 12.

SUMMARY AND CONCLUSIONS

An analytical method for predicting the service life of laminated elastomeric bearings based on finite element analysis has been demonstrated. This method has shown generally good agreement with experimental results. The analytical method makes use of superposition to combine out-of-phase strain vectors and quasi three-dimensional strain analysis to find the endurance strain of complex bearings undergoing complex loadings. Limitations on superposition were indicated (shell stress in the spherical bearing). Finally a specific elastomer endurance relationship was drawn from test data on a fatigue specimen. With this background the analytic analysis provided a reasonable estimate of the location and time of first damage on the Blackhawk main rotor spherical and thrust bearings tested as part of this program. Good results were obtained in predicting the endurance life of the metal shells in the thrust bearing but, a prediction was not possible for the spherical bearing.

Future investigations in elastomeric bearing analysis could involve the study of some of the following areas:

A) Three-dimensional finite element analysis.

B) The effect of the bias strain on endurance life.

C) The effect of temperature on endurance life.

D) The effect of strain rate on endurance life.

E) The strain-relaxation characteristics of elastomers under constant and varying loads.

F) The effect of environmental media on the endurance life of elastomers.

G) The measurement and control of the physical properties of the elastomer.

H) The development of a three-dimensional shear strain endurance life criterion for elastomers.

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SERVICE LIFE DETERMINATION FOR
UH-60A (BLACKHAWK) HELICOPTER
ELASTOMERIC BEARINGS

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Technical Report AVRADCOM-80-F-8, April 1980,
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AMCMS Code 1498.94.587095 (YYS)

A method is shown for using finite element strain data and elastomer endurance data to predict the service life of elastomeric bearings. The method was demonstrated on the UH-60A (Blackhawk) helicopter main rotor bearings. These bearings were then tested to determine the degree of correlation between analytical and test results. Photographic documentation is given for the damage seen on the elastomeric bearings as a guide in establishing a bearing life criterion based on bearing appearance.

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Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
SERVICE LIFE DETERMINATION FOR
UH-60A (BLACKHAWK) HELICOPTER
ELASTOMERIC BEARINGS

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